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NUMERICAL MODELLING FOR THE URL BUFFER/CONTAINER EXPERIMENTS

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H.S. Radhakrishna, Senior Engineer
K.C. Lau, Engineer
Soil Sciences Section
Civil Research Department

ABSTRACT

Three computer codes were developed by the Civil Research Department of Ontario Hydro to assess the thermohydraulic performance of the buffer in the borehole emplacement concept. The TRUCHAM code models the coupled heat and moisture regime in the buffer and backfill while the TISDA-I and II codes model the stress-deformations induced by the moisture redistribution in the buffer. This report contains an overview of the development of numerical models and their application to the proposed buffer/container experiments at URL. The thermohydraulic transport coefficients required for the sensitivity analysis were determined by the laboratory experiments. The needs for further development of the models and determination of the material properties are identified.

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To Mr. D.W. Souther
Manager
Nuclear Engineering Department
Design and Development Division - Generation

Attn: Dr. S.J. Naqvi

**NUMERICAL MODELLING FOR THE
URL BUFFER/CONTAINER EXPERIMENTS**

1.0 INTRODUCTION

The Canadian concept for nuclear fuel waste disposal is to package the waste in corrosion-resistant containers, and to emplace them in a vault mined deep into the plutonic rock of the Canadian shield.

Two methods which have been proposed for placing the waste in the vault are in-room emplacement (TEC-1 design) and borehole emplacement (TEC-2) (Figure 1). For in-room emplacement, the waste filled containers will be placed on a bed of prepared buffer, with additional buffer being packed around and above them. The remaining volume would then be backfilled. In the borehole emplacement method, each container will be placed in a borehole drilled in the floor of the vault and the annular space will be filled with compacted buffer. Then the total volume of the drift will be backfilled.

Considering a scenario that the disposal vault will be operated for several years and maintained in a dry or semi-dry condition, the emplaced buffer in the disposal rooms will undergo an initial phase of thermal drying. This will be followed by a wetting phase as the disposal vault is sealed and the groundwater regime is allowed to re-establish itself. The drying phase can be critical to the overall performance of the buffer because it tends to degrade the thermal properties and cause shrinkage cracking of the buffer. The formation of such cracks could affect the integrity of the buffer as an engineered barrier. During re-establishment of the hydrostatic conditions in the vault, the buffer and backfill will get saturated. The bentonite clay in the buffer and backfill is expected to swell and heal the desiccation cracking developed during the drying phase.

In situ buffer/container experiments will be conducted at the Underground Research Laboratory (URL) to examine the buffer-container interaction for the TEC-2 design under a realistic geologic setting and thermal loading. Two experiments simulating the TEC-2 borehole emplacement design will be performed in a specially excavated room at the 240 m level in the URL. The thermal loading from the waste container will be simulated by an electric heater.

The first test is designed to investigate the performance of the engineered buffer barrier under a constant heat output from the heater and under the natural hydraulic boundary conditions at the borehole wall. This test will simulate the anticipated condition prior to the backfilling and sealing of rooms.

In the second test, the performance of the buffer under a constant heat flux from the heater and a controlled water recharge from the borehole wall will be investigated. This test will commence with the application of a constant heat flux at the heater, without water supplied at the buffer/heater interface boundary. After the thermal regime within the system has approached equilibrium, water from a recharge system will be allowed to saturate the buffer. This test will simulate the expected long-term condition of the buffer in a disposal vault environment/1/.

In this report, the status of the numerical modelling program supporting the URL buffer/container experiments is presented.

2.0 NUMERICAL MODELLING OF BUFFER PERFORMANCE

The principle processes that take place in the buffer under the imposed thermal and hydraulic conditions of the above buffer/container experiments are:

- 1) Heat transfer through the buffer.
- 2) Moisture migration through the buffer induced by a thermal gradient.
- 3) Moisture uptake through the buffer due to artificial recharge from the borehole wall.
- 4) Volumetric changes (swelling/shrinkage) associated with moisture redistribution in the buffer.
- 5) Stresses changes within the buffer due to a change in the moisture content of the buffer.
- 6) Stresses changes induced by the thermal expansion of the buffer.
- 7) Canister movement caused by the change in stiffness of the buffer.

As a result of thermal gradients imposed by heat generated from waste, moisture migration will occur in the buffer. This redistribution of moisture changes the thermal conductivity of the buffer, which in turn alters the thermal gradients in the buffer. Thus a coupled heat and moisture transport process is set up within the buffer.

Thermal expansion, and shrinkage/swelling induced by moisture migration can cause volume changes in the buffer. Based on the available material properties data and the thermohydraulic boundary conditions in a disposal vault, it is inferred that the volume changes due to thermal expansion of the buffer will be much smaller than the volume changes caused by the change in moisture content. Therefore, the effect of thermal expansion of the buffer can be ignored.

The thermal conductivity of the buffer is a function of its moisture content and density. In this research program, the relationship between the thermal conductivity and moisture content was determined by a stage drying test with the thermal needle technique. The change in thermal conductivity values due to the change in density of the buffer is being considered implicitly by the change in moisture content of the buffer. It is proposed to uncouple the effect of volume change from the heat and moisture migration process. If the results from the proposed buffer/container experiments indicate that the coupling effect between volume change, and heat and moisture migration is significant, then a new model has to be developed.

Since the reference buffer is well compacted and is confined within the borehole, the canister movements are anticipated to be negligible. Therefore in this study, the canister movement due to the change in the buffer stiffness caused by the change in moisture content will not be considered in this study.

Based on the above discussion, the objectives for this numerical modelling program are as follows:

- 1) Develop a suitable model to study the heat and moisture migration process within the buffer.
- 2) Develop a simple model to study the volume changes in the buffer due to the change in moisture content.
- 3) Develop computer codes for the above models.
- 4) Develop a data base for the material properties required in the model through a literature review or laboratory testing.
- 5) Carry out a sensitivity analysis to assist the design of the buffer/container experiments.

- 6) Perform pre-test predictions of the temperature and moisture fields in the buffer.

A long range modelling development program, including pre-test and post-test computations, material property determination, and computer code development is shown in Tables Ia, Ib, and II.

3.0 HEAT AND MOISTURE TRANSPORT MODELLING

The thermal conductivity of a soil is a function of its moisture content/2,3/. Under temperature gradients, the moisture in a soil medium tends to redistribute which in turn alters the thermal properties and the thermal regime. Thus a coupled heat and moisture transport is set up in partially saturated media/4,5,6/. Such a moisture migration phenomenon leading to thermal drying and shrinkage of the buffer could affect the following performances of the buffer:

1. The ability of the buffer to dissipate heat from the canister to the surrounding rock by the drop in its thermal conductivity.
2. The integrity of the buffer as an engineered barrier by the formation of shrinkage cracks.

Thermally induced soil water movement in unsaturated soils is a complex phenomenon. Several analytical models have been developed by researchers from both soil science and geotechnical engineering fields/7,8,9,10/. At present the major difficulty in applying these models is the lack of data on the transport coefficients or parameters involved in the governing equations.

3.1 Model Review

During the past three decades, many researchers using different approaches, have formulated the thermal induced moisture migration phenomenon into various sets of governing equations. Because of the complexity of the problem and the coupling effect involved, numerical techniques were used to solve the various sets of governing equations. In Table III, a summary of the available computer codes is presented. The approaches used to formulate the problem can be classified into two main groups as; the mechanistic (or physical) approach, and the mathematical approach. The models developed by Philip and deVries, and Dakshanmurthy and Fredlund are based on the mechanistic approach/11,12/. The model proposed by Taylor and Cary, based on the law of irreversible thermodynamics, follows the mathematical approach/13/.

3.1.1 Mechanistic Approach

Based on Fick's law, Philip and deVries proposed the following set of governing equations to describe the phenomenon of heat and moisture flow through a porous medium/11/.

$$\partial \theta / \partial t = \nabla \cdot (D_T \nabla T) + \nabla \cdot (D_\theta \nabla \theta) + \partial k / \partial z \quad (1)$$

$$\partial T / \partial t = \nabla \cdot (\lambda \nabla T) - L \nabla \cdot (D_{\theta \text{ vap}} \nabla \theta) \quad (2)$$

where ∇T = thermal gradient

$\nabla \theta$ = volumetric moisture content gradient

θ = volumetric moisture content

T = temperature

k = hydraulic conductivity

c = volumetric heat capacity

λ = thermal conductivity

$D_T = D_{T \text{ liq}} + D_{T \text{ vap}}$

$D_{T \text{ liq}}$ = thermal liquid diffusivity

$D_{T \text{ vap}}$ = thermal vapour diffusivity

$D_\theta = D_{\theta \text{ liq}} + D_{\theta \text{ vap}}$

$D_{\theta \text{ liq}}$ = isothermal liquid diffusivity

$D_{\theta \text{ vap}}$ = isothermal vapour diffusivity

Philip and Devries also developed a procedure for calculating the diffusivity parameters from the soil parameters and physical constants. The diffusivity terms are calculated from the experimental data and the physical properties of water and gas. In their model, the soil moisture is driven by both moisture content gradient and the temperature gradient.

By incorporating the heat flow equation with the two governing equations for moisture flow through unsaturated soil under isothermal condition, a heat and moisture flow model was developed by Dakshanamurthy and Fredlund./12/ They proposed that a temperature gradient in an unsaturated soil produces a change in the pore-air pressure which causes flow in the air-phase. The change in pore-air pressure in turn produces a change in the pore-water pressure, inducing a gradient in the water phase. The governing equations of their two-dimensional model are:

$$\partial T / \partial t = a_1 \partial^2 T / \partial x^2 + a_2 \partial^2 T / \partial y^2 \quad (3)$$

$$\partial U_w / \partial t = C_w \partial U_a / \partial t + C_{v1}^w \partial^2 U_w / \partial x^2 + C_{v2}^w \partial^2 U_w / \partial y^2 \quad (4)$$

$$\partial U_a / \partial t = C_a \partial U_w / \partial t + C_{v1}^a \partial^2 U_a / \partial x^2 + C_{v2}^a \partial^2 U_a / \partial y^2 \quad (5)$$

where U_a = pore-air pressure

U_w = pore-water pressure

T = temperature

a_1 = thermal diffusivity factor in the "x" direction

a_2 = thermal diffusivity factor in the "y" direction

C_w = interactive constant associated with the water phase equation

C_{v1}^w = coefficient of consolidation for the water phase with respect to the "x" direction

C_{v2}^w = coefficient of consolidation for the water phase with respect to the "y" direction

C_a = interactive constant associated with the air phase equation

C_{v1}^a = coefficient of consolidation for the air phase with respect to the "x" direction

C_{v2}^a = coefficient of consolidation for the air phase with respect to the "y" direction

By solving the heat flow equation with a finite difference scheme, the spatial and temporal change in temperature within the soil domain are computed. The temperature changes in the soil are converted to a change in pore-air pressure by the ideal gas law equation. The changes in pore-air pressure produce changes in the pore-water pressure in accordance with the pore pressure parameter defined in geotechnical engineering. Subsequently, the pore-air and pore-water pressures within the medium are computed by solving equations 4 and 5 simultaneously.

3.1.2 Mathematical Approach

Based on the law of irreversible thermodynamics, Taylor and Cary proposed the following linear equation to describe the phenomenon of heat and moisture flow through a particulate medium/13/.

$$J_i = \sum_{k=1}^N L_{ik} X_k \quad (i = 1, 2, \dots, N) \quad (6)$$

where J_i = flux or flow of the i^{th} component of the system
 L_{ik} = the phenomenological coefficient due to the k^{th} driving force affecting the i^{th} flux
 X_k = the driving force of the k^{th} component
 N = the number of driving forces

In order to apply the above equation to simulate the heat and moisture flow problem, the phenomenological coefficients involved have to be defined and computed with data measured from laboratory experiments.

By considering a closed soil-water system having an imposed temperature gradient at a steady state condition, Taylor and Cary simplified the governing equation to

$$q = -D_\theta \left[d\theta/dx + \beta^* d(\ln T)/dx \right] \quad (7)$$

where q = net water flux
 x = distance along the column
 T = absolute temperature
 β^* = $-d\theta/d(\ln T)$
 D_θ = $(D_{\theta \text{ liq}} + D_{\theta \text{ vap}})$ = the net effect of the liquid and vapour diffusivity terms

Based on the results of the experiments on samples of unsaturated Columbia fine sand loam, Cassel et al concluded that the Philip and deVries model showed acceptable agreement of the predicted and observed water movement/14/. The modified Taylor-Cary equation under-predicted the observed water movement.

Recently, Yong and Xu/15/ based on an identification technique, developed a method for determining the phenomenological coefficients in Equation 6 from the results of laboratory experiments/16,17/.

Using the experimental data from Cassel et al/14/, Yong and Xu/16,17/ computed the apparent isothermal and thermal diffusivity values for the Columbia fine sand loam. A general agreement was obtained with the results from Philip and deVries, and Cassel et al. However, some anomalies in the calculated isothermal diffusivity values were found between the three research groups.

3.2 Model Selection

In the selection of a model for the study of the thermal performance of the TEC-2 design, the following criteria are considered.

1. Ability of the model to include the coupled heat and moisture flow process in the reference buffer material.
2. Ability to measure the parameters or coefficients involved in the governing equations of the model for the reference buffer material without great difficulty.
3. Ability of the computer code to consider complex 3-D boundary conditions.

Dakshanamurthy and Fredlund in their model assumed that the continuity of the air-phase exists within the soil. At higher saturation, the air-phase becomes occluded and the model requires modification. Also, their model did not include the coupling effect of moisture redistribution on the thermal regime. Considering that the buffer will be subjected to drying and resaturation conditions in the underground repository, and because of the importance of the coupling effect, the Dakshanamurthy and Fredlund model is not suitable for this study.

The governing equations in the Philip and deVries model and the Taylor and Cary model have similar form. Thus a single computer code can be developed for both of these models. The main difference between the two models is in the method used for determining the transport coefficients. Philip and deVries in their model proposed a method of computing some of the transport coefficients using a capillary model and physical constants for liquids and gases. Taylor and Cary used the results of a one-dimensional heat and moisture diffusion experiment to extract the transport coefficients.

The reference buffer is a bentonite-sand mixture. The swelling properties of the clay adds a new complexity in modelling the heat and moisture flow by using the governing equations proposed by Philip and deVries. It is proposed to circumvent this problem by extracting the moisture transport coefficients from the laboratory test results on the reference buffer. Thus the effects of swelling are included in the lumped parameters.

However, the simplified laboratory experiments used to obtain the coefficients may not fully represent the field conditions. Such differences between the field and laboratory conditions may affect the accuracy of the model to predict the field performance, and some anomalies may occur. If that is the case, the buffer/container experiment results have to be used to back calculate the soil parameters for the model.

3.3 The Computer Code

Equations 1 and 2 describe the heat and moisture transfer in unsaturated soils. In view of the coupling effect between Equations 1 and 2 and the non-linear material properties involved, no exact solution can be obtained for most practical situations.

To solve these governing equations, a computer code, TRUCHAM was developed at Ontario Hydro/18/ which utilizes an integrated finite difference technique. It can accommodate a variety of linear and non-linear boundary conditions and material properties.

The special features of this program are: (i) it can deal with coupled heat and moisture induced flow; (ii) it can accommodate a wide variation of material properties; (iii) its formulation in multidimensionals (1 to 3) space is relatively simple, and (iv) there is an automatic choice of time step to ensure the stability and convergence of the numerical solution/18/. Because the governing equations for the Philip and deVries model, and for the Taylor and Cary model are similar in form, the computer code can be used to describe both models.

3.4 Material Properties

The thermohydraulic material properties were determined McGill University, Carleton University, and Ontario Hydro. At McGill University, laboratory tests were conducted to determine the phenomenological coefficients for the Taylor and Cary model. In addition, the reference buffer's thermohydraulic material properties were calculated according to the method proposed by Philip and deVries. The thermohydraulic material properties for the reference buffer were determined at Carleton University by applying Young and Xu's identification technique.

At Ontario Hydro, the thermohydraulic material properties of the buffer were determined by 1-D isothermal and non-isothermal experiments. A description of the various techniques used and the results obtained are presented in the following sections.

3.4.1 Work Done at McGill University

Yong and Xu developed a method to calculate the phenomenological coefficients for the Taylor and Cary model, based on an identification technique /15/. The same technique was used by Selvadurai/19/ to determine the material properties for the Philip and deVries model. In their technique, a set of basic functions are selected to describe the relationship between the phenomenological coefficients and the variables (temperature and moisture content.) By matching the results from experiments, the phenomenological coefficients are calculated by a computer program. This technique is extremely versatile but its main drawback is that the calculated coefficients are highly sensitive to the type of functions used in the calculation. Appropriate type of functions for a swelling clay are not yet known.

The preliminary data obtained from their experiments are presented in Figures 2, 3 and 4. These experiments are still in progress.

3.4.2 Work Done at Carleton University

By applying the Yong and Xu's identification technique to the Philip and deVries governing equations, Selvadurai/19/ determined the thermohydraulic material properties for the reference buffer. Based on the preliminary results from his study, the following expressions for thermohydraulic diffusion coefficients were developed:

$$\begin{aligned}D_{\theta} &= (1.803 + 0.138T)e^{1.955\theta} \times 10^{-4} \text{ (cm}^2\text{/sec)} \\D_T &= (-2.216 + 0.375T - 2.833\theta) \times 10^{-7} \text{ (cm}^2\text{/sec/}^\circ\text{C)} \\D_{\theta \text{ vap}} &= (-0.226 + 0.036T - 2.889\theta) \times 10^{-7} \text{ (cm}^2\text{/sec)} \\ \lambda &= 1.5 \times 10^{-2} \text{ (w/cm/}^\circ\text{C)}\end{aligned}$$

and the average values for coefficients over the temperature and moisture ranges used in their tests are:

$$\begin{aligned}D_{\theta} &= 13.82 \times 10^{-4} \text{ (cm}^2\text{/sec)} \\D_T &= 9.28 \times 10^{-7} \text{ (cm}^2\text{/sec/}^\circ\text{C)} \\D_{\theta \text{ vap}} &= 0.92 \times 10^{-7} \text{ (cm}^2\text{/sec)} \\ \lambda &= 1.5 \times 10^{-2} \text{ (w/cm/}^\circ\text{C)}\end{aligned}$$

The relationship between the thermohydraulic properties, temperature and volumetric moisture content are plotted in Figures 5, 6 and 7.

3.4.3 Work Done at Ontario Hydro

In view of the uncertainty involved in the identification technique, Ontario Hydro determined the diffusivity parameters required in the Philip and deVries model from the specially designed 1-D experiments.

Equation (1) can be rewritten as:

$$q_{vap}/\rho_w = D_T \nabla T - D_\theta \nabla \theta \quad (8)$$

For isothermal conditions,

$$q_{vap}/\rho_w = -D_\theta \nabla \theta \quad (9)$$

or

$$D_\theta = - q_{vap}/(\rho_w \nabla \theta) \quad (9A)$$

The D_θ values were calculated from the results of one-dimensional isothermal moisture diffusion experiments. The setup of the experiments is shown in Figure 8. The effect of temperature on D_θ value was determined by conducting experiments under different elevated ambient temperature.

At steady state, equation (1) can be written as:

$$D_T \nabla T = D_\theta \nabla \theta \quad (10)$$

or

$$D_T = D_\theta (\nabla \theta / \nabla T) \quad (10A)$$

By applying a thermal gradient along a buffer column (Figure 9), at steady state, the D_T at various temperatures and moisture contents can be calculated.

At steady state, equation (2) can be written as:

$$\lambda \nabla T = LD_{\theta \text{ vap}} \nabla \theta \quad (11)$$

or

$$D_{\theta \text{ vap}} = \lambda \nabla T / L \nabla \theta \quad (11A)$$

Thus by inputting the thermal conductivity values into equation (3), the $D_{\theta \text{ vap}}$ value of the buffer was calculated. The results of the thermohydraulic material properties determined in this manner are shown in Figures 10 and 11.

A comparison between the results obtained by McGill University, Carleton University and Ontario Hydro is presented in Figures 12 and 13. The values for the thermohydraulic properties measured by different techniques fall within the following range:

$$\begin{aligned} D_{\theta} &= 1 \times 10^{-4} \text{ to } 5 \times 10^{-6} \text{ (cm}^2\text{/sec)} \\ D_T &= 5 \times 10^{-7} \text{ to } 6 \times 10^{-9} \text{ (cm}^2\text{/sec/}^\circ\text{C)} \\ D_{\theta \text{ vap}} &= 2 \times 10^{-7} \text{ to } 2 \times 10^{-10} \text{ (cm}^2\text{/sec)} \end{aligned}$$

All of the experiments described above were conducted on specimens of reference buffer material (50% sand and 50% Avonlea bentonite) compacted to a reference dry density of 1680 kg/m^3 at a reference moisture content of 18.3%.

Thermal conductivity values of the reference buffer were determined by the line source heat conduction technique. The thermal conductivity of the reference buffer material is found to be strongly dependent on its moisture content as shown in Figure 14. For the pre-test modelling purpose, data produced for a crushed granite-bentonite mixture is used/2/.

3.5 Model Validation

From the above discussions on model selection and material properties to be used, the current strategy consists of solving the governing equations of the type proposed by Philip and deVries (Equations 1 and 2) by using the material properties (D_{θ} , D_T) determined from one-dimensional heat and moisture flow experiments.

In order to verify the soundness of this strategy, the case of a single heater experiment completed by Carleton University in a granite block was simulated by the TRUCHAM model by using the reference buffer material properties given in Figures 12 to 14. The results of this analysis are summarized in a separate report/20/.

The main conclusions of this study are/20/:

- 1) The heat and moisture coupling effect is significant and should be included.
- 2) The temperature and moisture regimes in the buffer/container experiment No. 1 can be predicted with a sufficient degree of confidence.

3.6 Scoping Calculations and Sensitivity Analysis

The near-field temperature and moisture regimes in the buffer and rock mass was modelled for the proposed URL buffer/container experiment #1 using the TRUCHAM computer code and the available material properties.

The modelling effect was initially directed to perform scoping calculations as an aid for the design of the buffer/container experiment #1/21/. This included:

- Selection of the power level at which the single heater has to be operated.
- Selection of instrumentation location.
- Assessing the effects of ambient room temperature and the geometry of the experiment room.

In the second stage of modelling, a sensitivity analysis was performed by varying the following material properties:

- The thermal conductivity of the sand in the annulus between the heater and the buffer.
- Hydraulic conditions at the buffer/rock boundary.
- Thermal conductivity of the buffer.
- Thermohydraulic properties of the buffer.

A fine element mesh would be required to detail the temperature and moisture content distribution around the heater and buffer (near-field). To properly represent the boundary conditions and to achieve the required accuracy in computation, a very large number of elements would have been required for this study. A simplified method consisting of a two stage computation was employed. In the first stage, the far-field (Figure 15) was discretized with a relatively coarse mesh. In the second stage, a finer mesh in the near-field was used (Figure 16), in which the temperature values determined from the first stage (the far-field analysis) and the specified moisture content values were imposed at

its external boundary. With such a technique, a more detailed temperature and moisture content distribution in the near-field was obtained with minimum computing cost. The cases analyzed are listed in Table IV.

The significance of the various parameters on the thermal performance of the buffer in the design of the buffer/container experiment #1 is presented in this section. As one of the functions of the buffer is the dissipation of the heat generated by the decay of radionuclides, the buffer's performance is evaluated in terms of the resulting heater/buffer contact temperature. Table IV summarizes the different cases analyzed with various combinations of boundary conditions and material properties.

1. Thermal Conductivity of the Buffer

The effect of the thermal conductivity of the buffer on the thermal performance of the system is shown in Figure 17. By comparing the cases of completely dry buffer (upper bound) and of moist buffer (lower bound) conditions, it can be concluded that the thermal drying of the buffer has a significant effect on the container temperature.

2. Ambient Temperature of the Experimental Room

The heater temperature versus time curves for the ambient experimental room temperature of 12 and 15°C are plotted in Figure 18. This indicates that the change in heater temperature is almost equal to the change in ambient room temperature.

3. Geometry of the Layout of the Experiment

A revision in the geometry of the experiment was made to account for the over excavation of the floor around the borehole for Experiment #1. The changes involved an increase in the thickness of the concrete floor slab by 400 mm and the reduction in the thickness of the sand and buffer below the heater by 100 and 700 mm respectively (Figure 19).

Figure 20 shows the predicted heater temperature versus time curves for Experiment #1 for both original and revised geometries. By comparing the heater temperatures from the two cases, it is seen that the revision in the test geometry has no significant effect on the thermal performance of the system.

4. Thermal Conductivity of the Sand between the Heater and Buffer

"Frac sand" was selected by AECL researchers at Whiteshell for backfilling the annulus space between the heater and buffer. The thermal conductivity values for this dry sand at various densities were determined in our laboratory and the results are shown in Figure 21. A change in the thermal conductivity value of sand from 0.004 to 0.003 w/cm/°C,

resulted in a 10°C increase in the peak heater temperature (between Cases 1 and 6). This suggests that the density of the sand has a significant effect on the performance of the system.

5. Hydraulic Boundary Conditions at the Interface Between the Borehole Wall and the Buffer

To assess the effect of hydraulic conditions at the boundary on the temperature and moisture regimes in the buffer, two cases were considered namely, permeable and impermeable rock-buffer boundaries. The permeable boundary is defined arbitrarily as a boundary having a constant volumetric moisture content of 0.35, at the buffer/rock interface, while the volumetric moisture content within the buffer is not allowed to exceed its saturation value of 0.4. For the impermeable boundary condition, no moisture flow across the boundary is allowed and the volumetric moisture content within the buffer is not allowed to exceed its saturation value of 0.4.

Cases 7 and 8, represent impermeable and permeable hydraulic boundary conditions respectively. The heater temperature versus time plots for both Cases 7 and 8 are shown in Figure 22. These plots clearly indicate a higher heater temperature for Case 8 than for Case 7 at times beyond 200 days. Such a rise in heater temperature indicates the occurrence of a thermal drying phenomenon within the system. With the occurrence of thermal drying of buffer, the heater temperature increases rapidly with time. The thermal drying by net loss of moisture in Case 8 is confirmed by the volumetric moisture content versus time plot shown in Figure 23. At 200 days, the volumetric moisture content of the buffer at 41 cm from the centre of the heater is reduced from its original value of 0.3 to 0.08. Beyond 200 days, further reduction in moisture content of the buffer is indicated. Figure 14 indicates that a reduction in thermal conductivity of the buffer commences when the volumetric moisture content of the buffer falls below a value of 0.08. Such a reduction in the buffer thermal conductivity will impede the heat dissipation through the buffer.

For Case 7, the volumetric moisture content versus time plots at various radial distances from the centre of the heater are shown in Figure 24. This figure clearly indicates that the volumetric moisture content of the buffer never gets below a value of 0.08. This is a result of the return moisture flow in the liquid phase due to the moisture build up at the impervious buffer-rock boundary.

6. Thermohydraulic Properties of the buffer

The thermohydraulic properties of the buffer used and the resulting heater temperature versus time plots for Cases 8, 9 and 10 are shown in Figure 25. A permeable hydraulic boundary condition as defined and a heater power of 1000 w were used.

No thermal instability phenomenon occurred for Cases 9 and 10 while for case 8 an order of magnitude increase in D_T resulted in a thermal instability in the buffer.

From the results of the above analyses, the following conclusions may be drawn:

1. Thermal drying of the buffer will have a very significant effect on the thermal performance of the buffer.
2. The proposed revision in geometry of the experiment has no significant effect on the experiment.
3. The change in heater temperature directly corresponds to the change in ambient room temperature.
4. The thermal conductivity of the sand annulus between the heater and the buffer significantly influences the heater temperature.
5. Thermally induced moisture migration will occur within the buffer.
6. Based on the material properties assumed in the analysis, extensive thermal drying of buffer can occur if the buffer/rock boundary is permeable for moisture to escape from the system.
7. Based on the material properties assumed in the analysis, about 80% of the total change in moisture content occurs in parts of the buffer adjacent to the heater within:
 - 30 days (with an impermeable buffer/rock boundary)
 - 80 days (with a permeable buffer/rock boundary)
8. Based on the material properties assumed in the analysis, about 80% of the total temperature rise of heater occurs within 10 days. The rate of change of heater temperature is much faster than that of the volumetric moisture content. Thus it will be possible to adjust the heater power during Experiment #1 without significant affect on the volumetric moisture content regime of the buffer.

3.7 Preliminary Heater Power Selection for Experiment #1

The results of the previous analysis are summarized in Figure 26. In this figure, the heater power versus the resulting heater temperature for the cases 1,2 and 11 are plotted.

At present, with the uncertainty associated with the thermal conductivity of the "Frac sand", the hydrogeological conditions at the buffer/rock interface, and the temperature of the experimental room, a heater power of 850 w is suggested for Experiment #1. It

is anticipated that with a heater power of 850 w, the resulting heater temperature may fall short of the target value of 85°C. However, this power is recommended so that the heater power can be increased if the measured heater temperature is below the target value of 68°C after 10 days. With the heater output at 850 w, even in the event of severe buffer drying, the resulting heater temperature will remain below the boiling point of water (Case 1, the upper bound solution).

3.8 Future Schedule

1. Pre-test Forecast

The results of these scoping calculations indicate that the thermal conductivity values of the "Frac sand" in the annulus between the heater and the buffer, and the hydraulic conditions at the rock boundary have a very significant effect on the thermal performance of the test. These factors have to be defined before any pre-test forecast can be made. It is anticipated that a pre-test forecast can be made for Experiment #1 in two weeks time once all the test conditions are established.

2. Model Development

In Experiment #2, resaturation of the buffer will be simulated by applying water under a moderate pressure around the buffer. After the buffer becomes saturated, the Philip and deVries model which uses the volumetric moisture content as the driving potential, will no longer valid. By changing the driving potential in the governing equations from moisture content to pressure head, the model can be used for both saturated and unsaturated flow conditions. In order to solve the governing equations in pressure head form, the suction versus moisture content relationship has to be established over the full range of temperature and moisture content. This requires laboratory measured data. This model development is scheduled for completion in 1991.

4.0 SHRINKAGE/SWELLING OF BUFFER/BACKFILL DUE TO THERMALLY INDUCED MOISTURE MIGRATION

A typical contour plot of volumetric moisture content in the buffer with a constant potential hydraulic boundary condition at the buffer/rock interface is shown in Figure 27.

For the purposes of developing a model to predict the shrinkage and swelling within the buffer and backfill due to moisture migration, the buffer can be separated into 2 regions. In region I around the heater, the moisture flow is in the radial direction, resulting in concentric rings of constant volumetric moisture content values. Above the heater in region II, the moisture flow is mainly in the vertical direction. Thus 2 simple models are proposed to predict the shrinkage and swelling of the buffer and backfill caused by moisture migration.

4.1 The Concentric Ring Model - Region I

In region I, a concentric ring model is proposed by making the following assumptions:

1. isotropic material properties,
2. the volumetric change in the buffer due to thermal expansion is negligible,
3. no volume changes take place in the sand annulus, and
4. a plane strain condition with radial symmetry.

The steps involved in the calculation of the stresses and deformations in the buffer due to moisture migration are listed in Figure 29. In Step 1, the volumetric moisture content values within the buffer can be obtained from either field measurement or from numerical predictions.

Based on the moisture content distribution, the buffer is discretized into concentric rings. In step 2, the volumetric change of each ring caused by a moisture change is calculated from the results of laboratory swelling/shrinkage tests. In step 3, a displacement continuity requirement is imposed at the interfaces between each ring, the contact between the buffer and rock, and the contact between the buffer and sand(heater). Based on this continuity requirement, the radial stresses at the interfaces between each ring are calculated. If the calculated radial stresses at the inner and outer boundaries of the buffer are tensile then these radial tensile stresses are set to zero (step 4), and the radial stresses at the interfaces between each ring are recalculated (steps 5 and 6). This iterative process will continue until the radial stresses at the inner and outer boundaries of the buffer become zero or compressive.

4.2 Radial Symmetric Disc Model - Region II

In region II, a radial symmetric disc model is used (Figure 30). The assumptions involved in the model development are:

1. Isotropic material properties.
2. The volumetric change of the buffer and backfill due to thermal expansion is negligible.
3. Uniform deformation in the Z direction.

The steps involved in the calculation of the stresses developed within the buffer/backfill due to moisture migration are shown in Figure 31. Initially, the buffer and backfill in region II (Figure 27) are discretized into discs of equal volumetric moisture content values. The model considers the vertical stresses between each disc, the radial stresses and frictional stresses between the disc and the borehole wall.

A computer program, TISDA-I (Thermal Induced Stress Deformation Analysis), has been developed for the concentric ring model for region I. The computer program for the radial symmetric disc model, TISDA-II, is still under development, to address the difficulties involved in the tracking of the direction of the shear stresses developed at the buffer/rock interface during the iterative process.

4.3 Material Properties

The following material properties are required for the above concentric ring and the disc models.

- 1) Volumetric swelling/shrinkage of the buffer as a function of its volumetric moisture content at various ambient temperatures.
- 2) The deformation modulus of the buffer as a function of its volumetric moisture content and density.
- 3) The tensile strength of the buffer as a function of volumetric moisture content.
- 4) The friction angle between the buffer and the host rock.

The test procedures to obtain the above material parameters are being developed in co-operation with AECL. This work is expected to be carried out at AECL, Ontario Hydro and the University of Manitoba.

4.4 Application of the Computer Code

In this section, the application of the model is demonstrated by considering the volumetric moisture content of the buffer calculated for Cases 7 and 8 at 500 days. The material properties used are as follow:

$$\begin{aligned} E_{\text{dry}} &= 400 \text{ MPa} \\ E_{\text{sat}} &= 20 \text{ MPa} \\ (\Delta V/V)/(\Delta \text{ moisture content}) &= 0.0011 \end{aligned}$$

The deformations in the buffer due to the change in volumetric moisture content were calculated using TISDA-I. For Case 8 with a permeable hydraulic boundary, a large

desaturation of the buffer is predicted. A circumferential tensile zone is predicted to extend $1/2$ of the distance from the surface of the heater to the buffer/rock boundary.

For Case 7 (impermeable hydraulic boundary), although no net reduction in total moisture within the buffer is predicted, formation of a tensile zone extending over $1/4$ of the thickness of the buffer from the heater to the buffer/rock boundary was calculated. These results indicate that there is potential for the development of tensile cracking in the buffer due to thermal drying, before resaturation.

This study demonstrates that numerical tools are available for predicting the deformation of the buffer/backfill system. However, there is a significant lack of data regarding the appropriate material properties required for these predictions.

5.0 CONCLUSIONS

To support the URL buffer/container experiments, three computer codes were developed. The computer code, TRUCHAM, is designed to study the heat and moisture transport through the buffer barrier under the thermal load. The computer code, TISDA-I and TISDA-II, are designed to study the stresses and deformations within the buffer due to the thermally induced moisture changes.

Using the TRUCHAM code, a sensitivity analysis on the factors affecting the performance of the URL buffer/container Experiment 1 was conducted. The following conclusions are drawn from this analysis:

- (a) Thermal drying of the buffer will have very significant effect on the thermal performance of the buffer.
- (b) The proposed revision in geometry of the experiment has no significant effect on the experiment.
- (c) The change in heater temperature directly corresponds to the change in ambient room temperature.
- (d) The thermal conductivity of the sand annulus between the heater and the buffer significantly influences the heater temperature.
- (e) Thermal drying of the buffer depends on the heater power and the thermohydraulic properties of the buffer.
- (f) A significant amount of thermal drying of the buffer can occur if the buffer/rock boundary is permeable for moisture to escape from the system.

(g) About 80% of the total moisture content change occurs in parts of the buffer adjacent to the heater within:

- 30 days (with impermeable buffer/rock boundary)
- 80 days (with permeable buffer/rock boundary)

(h) About 80% of the total temperature change occurs within 10 days. The rate of the heater temperature change is much faster than that of the volumetric moisture content. Thus it will be possible to adjust the heater power during the early stage of Experiment #1 without a significant effect on the volumetric moisture content regime in the buffer.

(i) A heater power of 850 w is recommended to achieve a target heater temperature of 85°C for Experiment #1.

To demonstrate the capability of the computer program TISDA-I, two cases were analyzed with assumed material properties. Based on these results the following conclusions are made:

- (j) The computer program TISDA-I can model the moisture-change-induced stresses and deformation in the buffer around the heater.
- (k) Only a limited amount of information is available on the deformation properties versus moisture content of the reference buffer. Research work in this area is urgently needed.
- (l) Further development of the computer program TISA-II is required to resolve the difficulties involved in tracking the direction of the shear stresses developed at the buffer/rock interface.

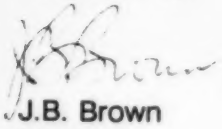
A pre-test forecast of the temperature and buffer moisture regime in the buffer will be performed after the definition of the thermal conductivity value of the sand between the buffer and the heater, and the hydraulic boundaries at the buffer/rock interface. The stress-deformations in the buffer region for Experiment #1 will be analyzed after the necessary development of TISDA-II and material property determinations are made in 1991.

ACKNOWLEDGEMENTS

The writers thank Dr. Bruce Kjartanson of AECL for his valuable comments. Technical input provided by Professor Adrian Crawford, of the University of Toronto, in developing computer codes TISDA-I and TISDA-II are highly appreciated. This project was carried

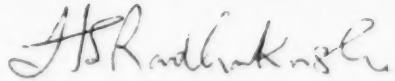
out under TAP by the Nuclear Engineering Department and was co-funded by the Research Division of Ontario Hydro.

Approved by:



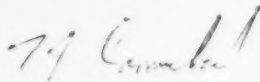
J.B. Brown
Manager
Civil Research Department

Prepared by:



H.S. Radhakrishna
Senior Engineer
Soil Sciences Section

Reviewed by:



T.J. Carmichael
Supervising Engineer
Soil Sciences Section



K.C. Lau
Engineer
Soil Sciences Section

HSR:KL/LM

REFERENCE

1. L.D. Kiel and B.H. Kjartanson. "Buffer/Container Experiment - Conceptual Design Report - Draft for Review and Comments." Sept 1989, AECL.
2. H.S. Radhakrishna. "Thermal Properties of Clay-Based Buffer Materials in a Nuclear Fuel Waste Disposal Vault". Atomic Energy of Canada Limited, Report No AECL-7805, 1984.
3. S.A. Boggs, F.Y. Chui, H.S. Radhakrishna and J.E. Steinmanis. (Ed) "Underground Cable Thermal Backfill". Proceedings of the Symposium on Underground Cable Thermal Backfill, Toronto, Canada, Sept 17 and 18, 1981.
4. J.G. Hartley and W.Z. Black. "Transient Simultaneous Heat and Mass Transfer in Moist, Unsaturated Soils". Trans American Soc Mech Eng, 103, 376- 382 (1981).
5. J.K. Mitchell. "Backfill Materials for Underground Power Cables, Phase 4: Theory and Field Testing of Backfill Thermal Stability". Department of Civil Engineering, University of California, Berkeley, EPRI, EL-4856, Oct 1986.
6. H.S. Radhakrishna. "Heat Flow and Moisture Migration in Cable Backfills". Ontario Hydro Research Quarterly, 20, No.2, 1986.
7. G.D. Aitchison, K. Russam and B.G. Richards. "Engineering Concepts of Moisture Equilibria and Moisture Changes in Soils, Moisture Equilibria and Moisture Changes in Soils Beneath Covered Areas". Review Panel Presentation, pp 7-21, Butterworth, Sydney, Australia, 1965.
8. B.J. Dempsey. "A Mathematical Model for Predicting Coupled Heat and Water Movement in Unsaturated Soil". Int J Numer Anal Methods Geomech, 2, pp 19-36, 1978.
9. M. Sophocleous. "Analysis of Water and Heat Flow in Unsaturated-Saturated Porous Media". Water Resources Research, 15, 1195-1206 (1979).
10. H.R. Thomas. "Modelling Two-Dimensional Heat and Moisture Transfer in Unsaturated Soils Including Gravity Effects". Int J Numer Anal Methods Geomech, 9, 573-588 (1985).
11. V. Dakshanmurthy and D.G. Fredlund. "A Mathematical Model for Predicting Moisture Flow in an Unsaturated Soil Under Hydraulic and Temperature Gradients". Water Resources Res, 17, 714-722 (1981).
12. J.R. Philip and D.A. deVries. "Moisture Movement in Porous Materials Under Temperature Gradients". EOS Trans AGU, 38(2), 222-232 (1957).

13. S.A. Taylor and J.W. Cary. "Linear Equation for Simultaneous Flow of Matter and Energy in a Continuous Soil System". *Soil Sci*, 28, 167-172 (1964).
14. R.N. Yong, A.M.O. Mohamed, F. Caporuscio, D.M. Xu and B. Wang. "Moisture Diffusivity in Buffer Material due to Temperature Gradients.", Third Progress Report, AECL PO=ws-28J-62996, Sept, 1989.
15. R.N. Yong and D.M. Xu. "An Identification Technique for Evaluation of Phenomenological Coefficients in Coupled Flow in Unsaturated Soils". *International Journal for Numerical and Analytical Methods in Geomechanics* Vol 12, pp 283-299. 1988.
16. R.N. Yong, A.M.O. Mohamed, F. Caporuscio, D.M. Xu and B. Wang. "Moisture Diffusivity in Buffer Material due to Temperature Gradients.", First Annual Report, AECL PO=ws-28J-62996, April, 1989.
17. D.K. Cassel, D.R. Nielson and J.W. Biggar. "Soil-Water Movement in Response to Imposed Temperature Gradients". *Soil Sci Soc Am J*, 33, 493- 500, 1969.
18. H.S. Radhakrishna, K.C. Lau and A.M. Crawford. "Coupled Heat and Moisture Flow Through Soils". *Journal of Geotechnical Engineering, ASCE*, Vol 110, No 12, pp 1766-1784. Dec 1984.
19. A.P.S. Selvadurai. "An Experimental Determination of the Parameters Governing Heat and Moisture Movement in a Clay-based Sealing Material". Department of Civil Engineering, Carleton University, 1989.
20. H.S. Radhakrishna and K.C. Lau. "Transient Unsaturated Coupled Heat and Moisture Flow Model Calibration". Ontario Hydro Report No. 90-////.
21. H.S. Radhakrishna and K.C. Lau. "Scoping Calculation for the URL Buffer/Container Experiment". Ontario Hydro Report No 89-47-K.

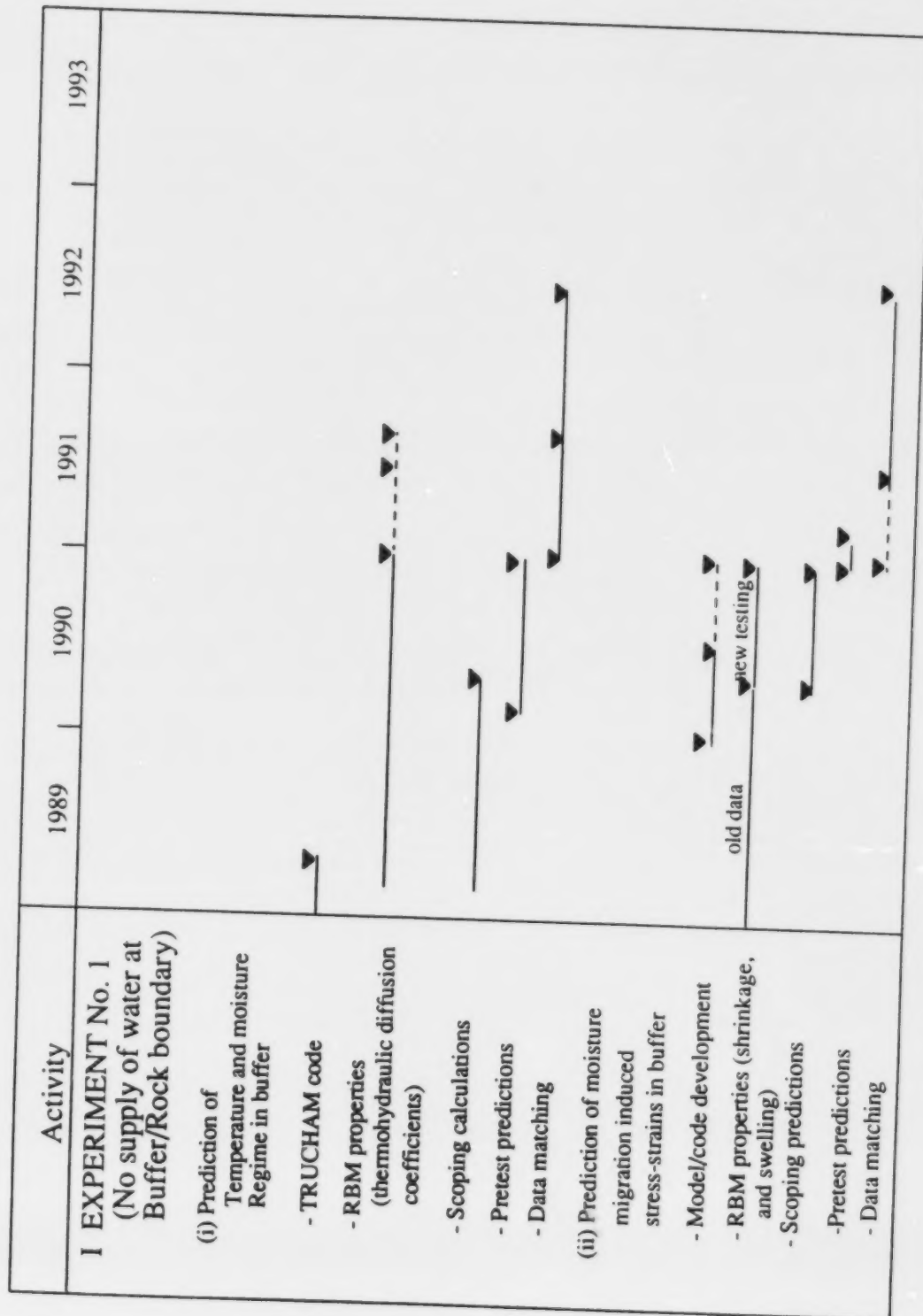


Table Ia Numerical Modelling for URL Buffer/Container Experiment No. 1

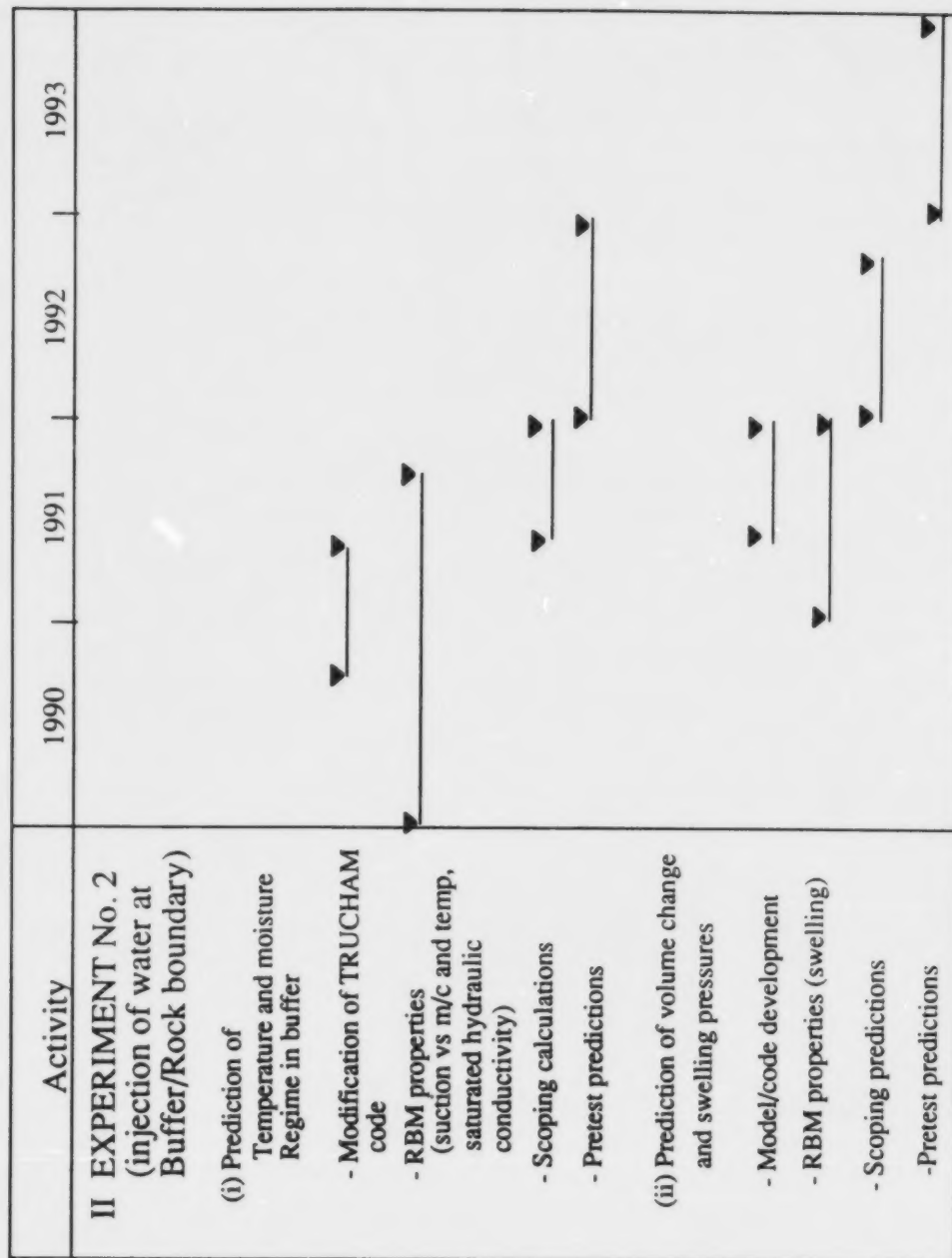


Table Ib Numerical Modelling for URL Buffer/Container Experiment No.2

<u>Parameter</u>	<u>Available Data</u>	<u>References</u>	<u>Planned Tests</u>	<u>Remarks</u>
Thermohydraulic conduction parameters (D_o , D_T , etc)		McGill Univ. Carleton Univ. Ontario Hydro Reports	Continue testing for water uptake	D_o were used for highly compacted bentonite in strippa tests
Suction vs m/c as a function of ambient temp. (20 to 80 degree C)	Limited data	McGill Univ. report	Continue testing	
Free swelling index as a function of vol. m/c (over 20 to 80 degree C)		WENRE test data (unpublished)	one-D swelling tests with water uptake	data needed urgently for scoping calculations
Vol. shrinkage as a function of m/c	(limited data)	WENRE test data	shrinkage tests (stage drying)	tests to be initiated at WENRE
Deformation modulus as a function of vol. m/c	none	-----	Ontario Hydro initiate uniaxial comp. tests	
Swelling pressure, vol. m/c and density relationship	no data available	-----	one - D swelling tests with compliance	not committed

Table II RBM Parameters for URL Buffer/Container Experiments

Table III Numerical Models

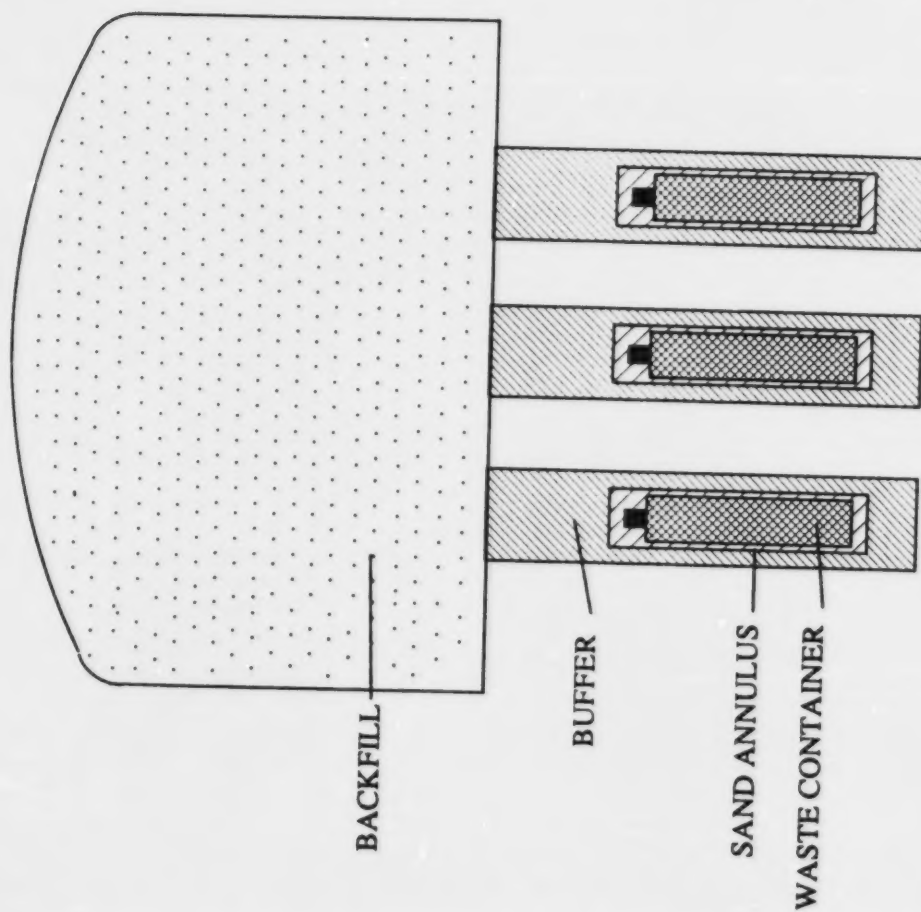
Author	Year	Solution Method	Dimensions	Type	Formulation Basis	Special Features and notes
Jury	1973	Kirchoff Transf. & Collocation	one	transient	θ, T	performed $\theta/\delta T$ experiments
Hartley	1977	FDH non-dim.	axi-sym.	transient	θ, T	predicts t/d^2 relationship predicts time to instability neglects gravity
Abdel-Hadi	1978	FDH	one	transient	θ, T	used "HEAT" to predict temp.
Bottomly	1978	FDH	one	transient	θ, T	two soil types allowed
Dempsey	1978	FDH implicit	two	transient	θ, T	can use weather data
Preece & Blowers Preece & Hichcock	1979	FDH implicit	axi-sym.	transient	θ, T	tridiagonal inversion logarithmic decay transform logarithmic timestep expanding mesh neglects gravity
Sophocleous	1979	FEM	one	transient & steady state	θ, T	can model heterogeneity, saturation, iso- and nonisothermal flows allows for thermally driven saturated flows Crank-Nicholson method used
Donazzi, Occhini and Seppi; Donazzi, Doench and Rosevear	1979 1981	conformal transform.	two	steady state	θ, T	predicts soil stability based on initial θ and VT general expression for resistivity as func. of θ neglects gravity
Dakshinamurthy and Fredlund	1980	FDH explicit	one	transient	θ, T	accounts for volume change
Soulsby and Dorevan	1981	FEM	two	transient and steady state	T	models temperature only intend to include θ modeling at a later date automatic mesh generation
Walker, Sabey and Hampton	1981	FEM implicit or explicit	two and axi-sym.	transient	θ, T	basis for present model
Milly	1982	FEM implicit	one	transient	θ, T	can model hysteresis, heterogeneity, heat of wetting storage matrices are diagonalized
Pruess and Wang	1983	IFDH	one, two or three	transient	p, T	employs steam tables uses Newton-Raphson iteration
Greeneveld, Snijders, Koopmans and Vermeer	1984		one	steady state	θ, T	general algorithms for $\theta(\theta, T)$ and $\lambda(\theta, T)$ hysteresis and temperature dependence of ϕ included calculates distribution of dry zone
Radhakrishna, Lau and Crawford	1985	IFDH mixed implicit-explicit	one, two or three	transient	θ, T	
Anders and Radhakrishna	1985	FEM	two	steady state	θ, T	uses advanced opacity-based algorithm operates on microcomputer

TEST CASE No.	Buffer Conditions k_t , W/cm degree c	Sand Annulus k_t , W/cm degree c	Rock/Buffer Hydraulic B.C.	Coupled Analysis		Remarks
				$D \Theta$ cm ² /sec	$D T$ cm ² /sec /K	
1	* ** dry - 0.007	* ** loose - 0.003	---	N/A		room temp. = 12 C
2	as compacted - 0.017	loose - 0.003	---	N/A		room temp. = 12 C
3	as compacted - 0.017	loose - 0.003	---	N/A		room temp. = 15 C
4	linear variation - dry to as compacted	loose - 0.003	---	N/A		room temp. = 12 C
5	0.007 - 0.017	loose - 0.003	---	N/A		room temp. = 12 C geometry change
6	dry - 0.007	dense - 0.004	---	N/A		room temp. = 12 C
7	moisture dependent	dense - 0.004	impermeable	5×10^{-5}	1×10^{-6}	room temp. = 12 C
8	moisture dependent	dense - 0.004	permeable	5×10^{-5}	1×10^{-6}	room temp. = 12 C
9	moisture dependent	dense - 0.004	permeable	5×10^{-5}	1×10^{-7}	room temp. = 12 C
10	moisture dependent	dense - 0.004	permeable	5×10^{-6}	1×10^{-7}	room temp. = 12 C
11	1/3 dry - 0.007 2/3 as compacted - 0.017	loose - 0.003	---	N/A		room temp. = 12 C

* Condition of the material

** k_t value of the material

Table IV Sensitivity Analysis and Scoping Calculations



TEC-2 DESIGN

Figure 1 TEC-2 design

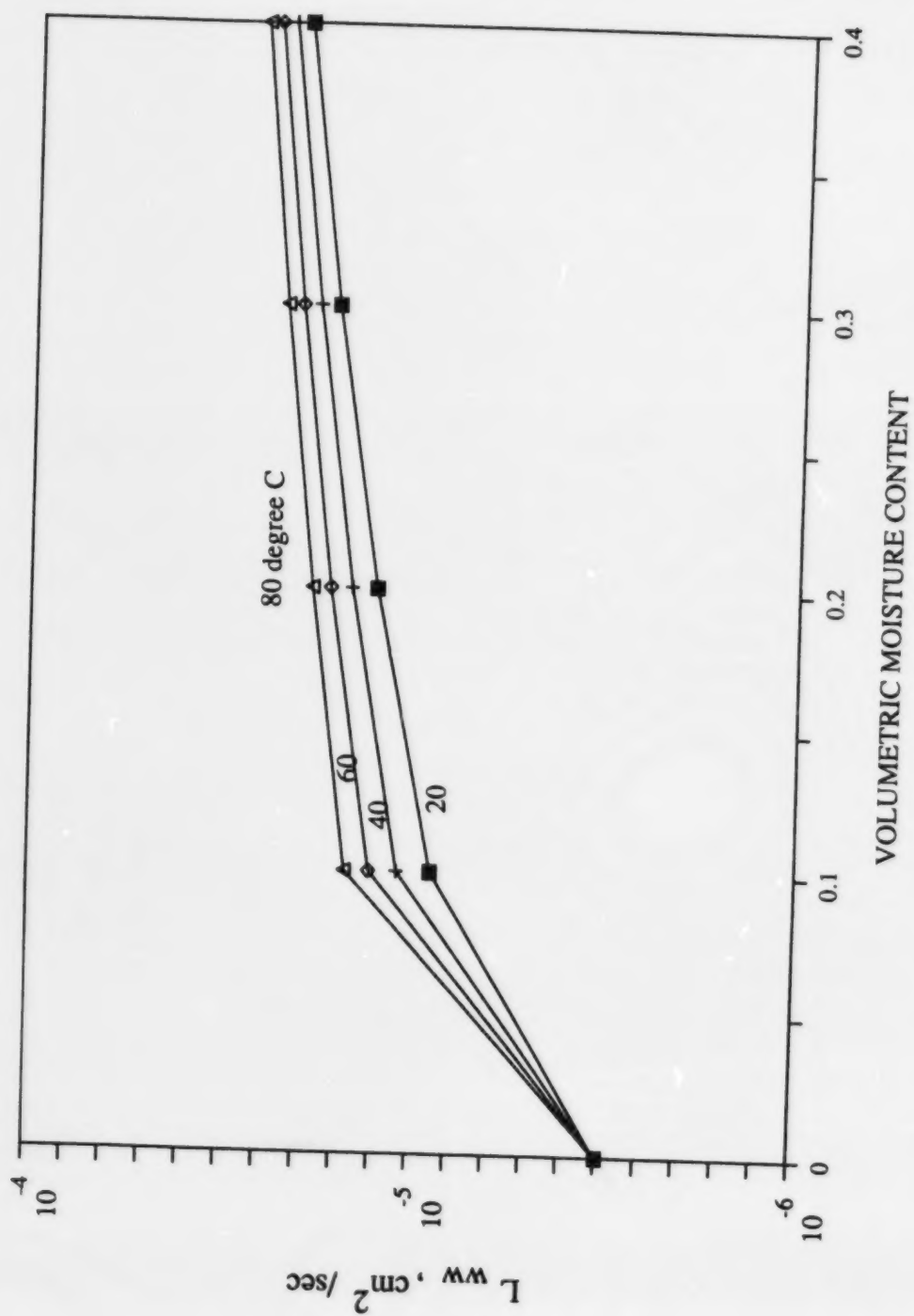


Figure 2 The L_{ww} values - McGill University

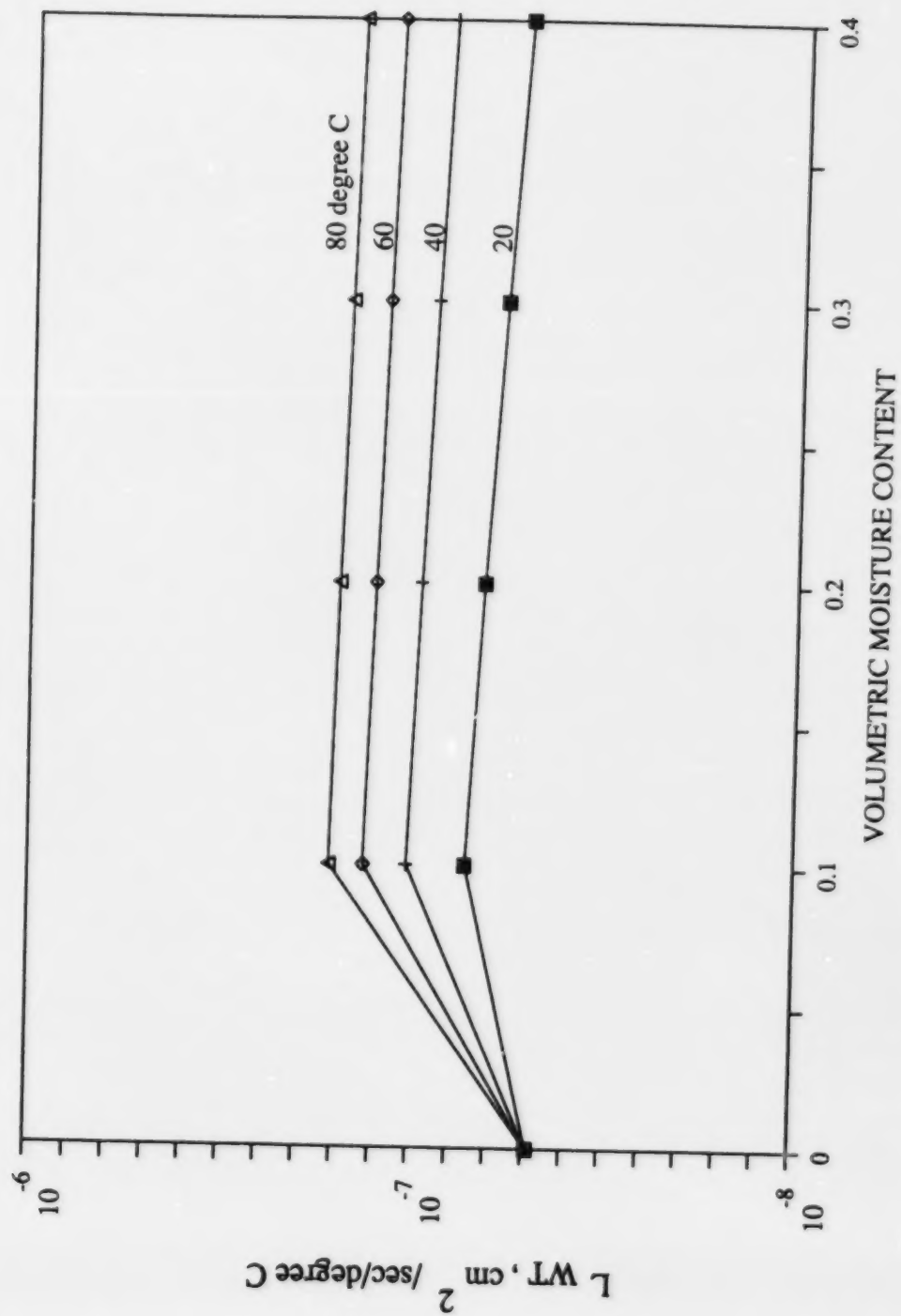


Figure 3 The L_{WT} values - McGill University

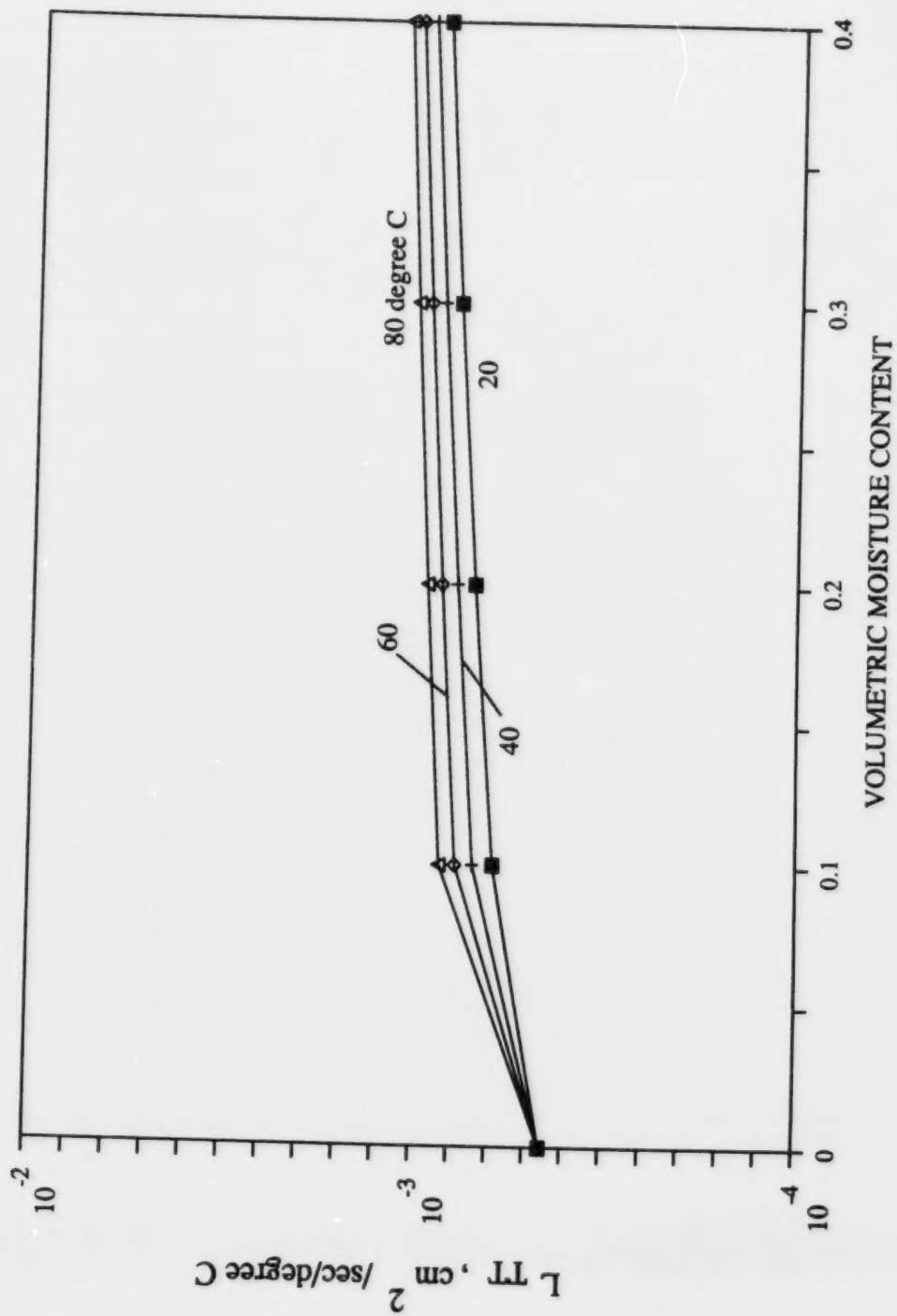


Figure 4 The L_{TT} values - McGill University

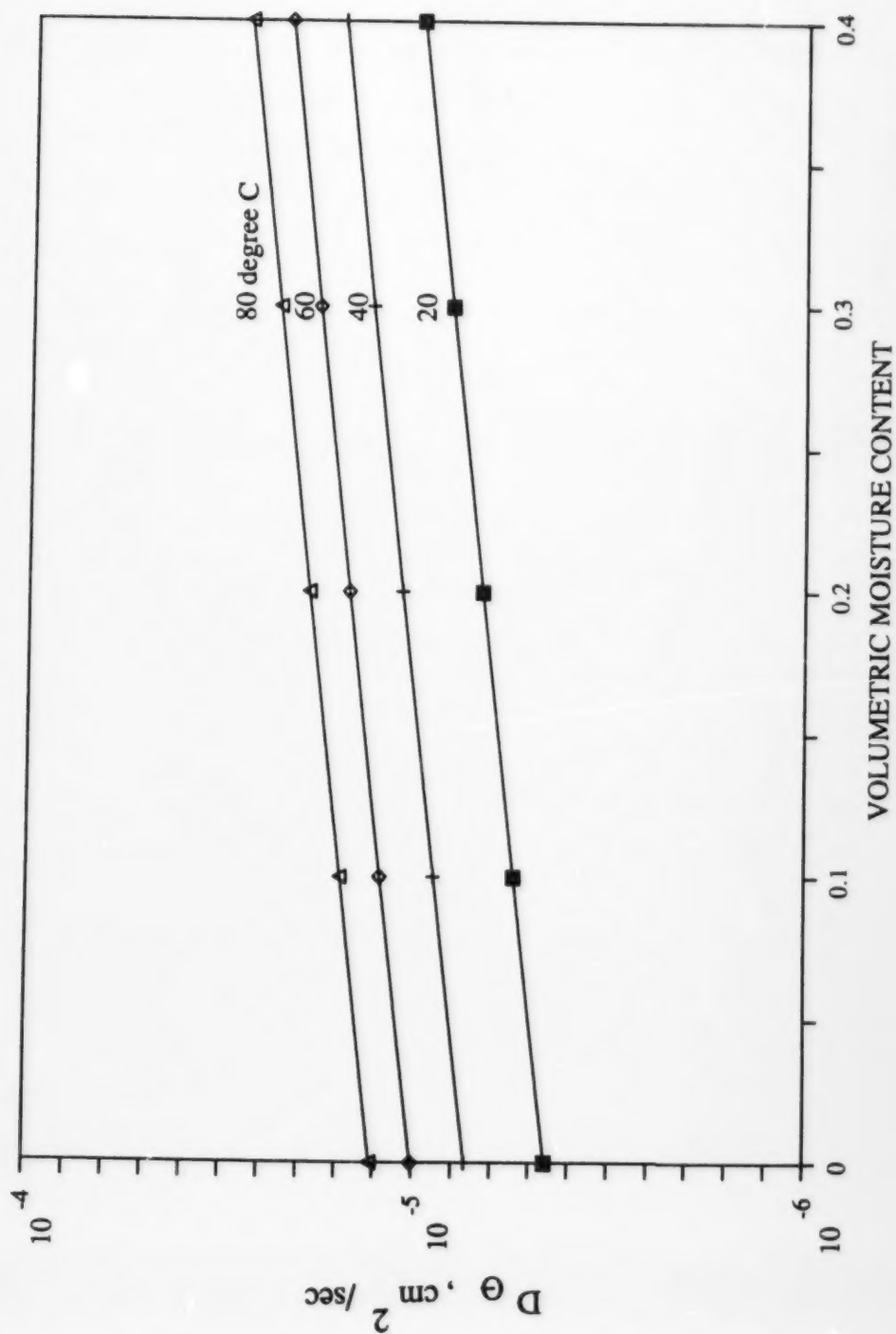


Figure 5 The D_{Θ} values - Carleton University

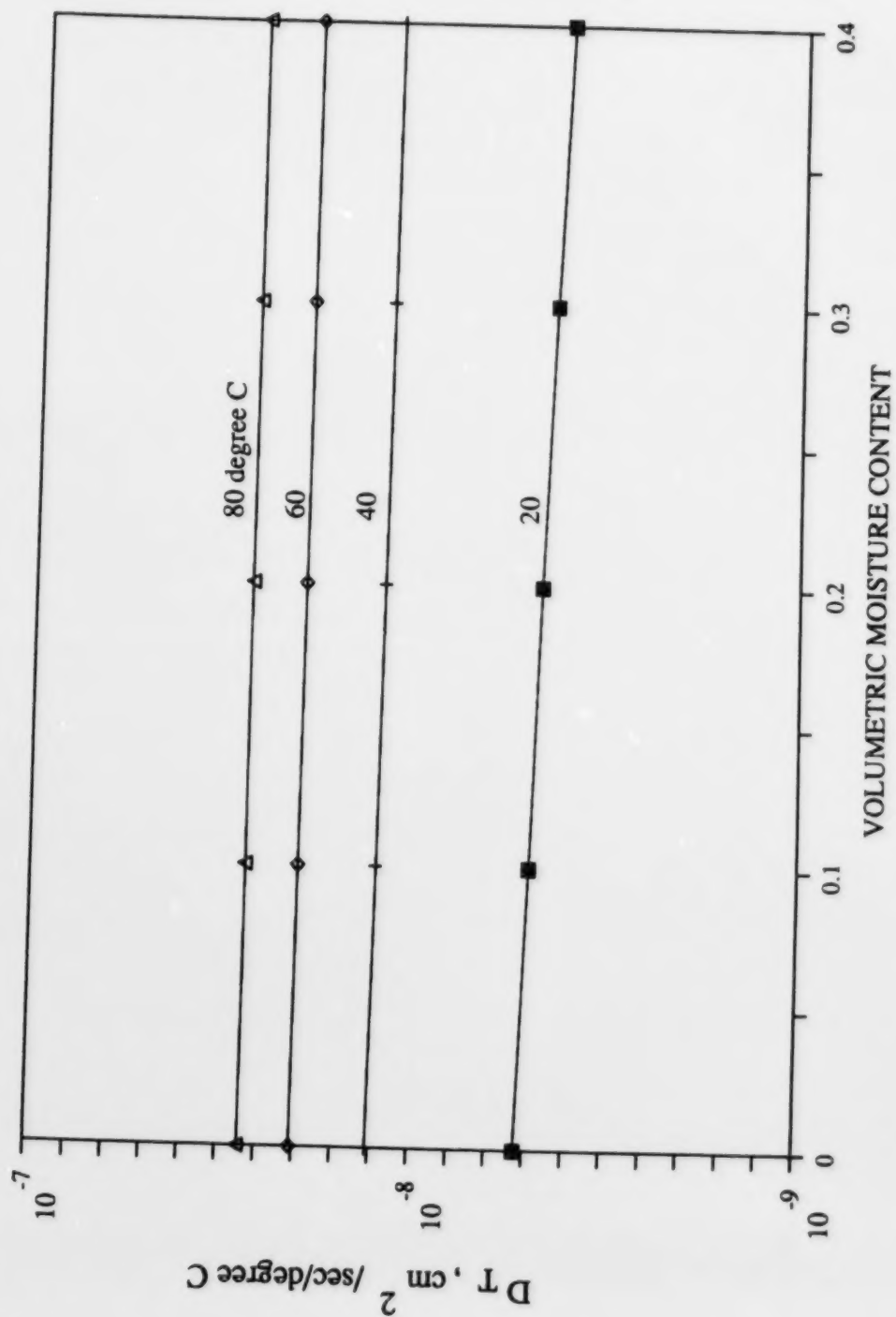


Figure 6 The D_T values - Carleton University

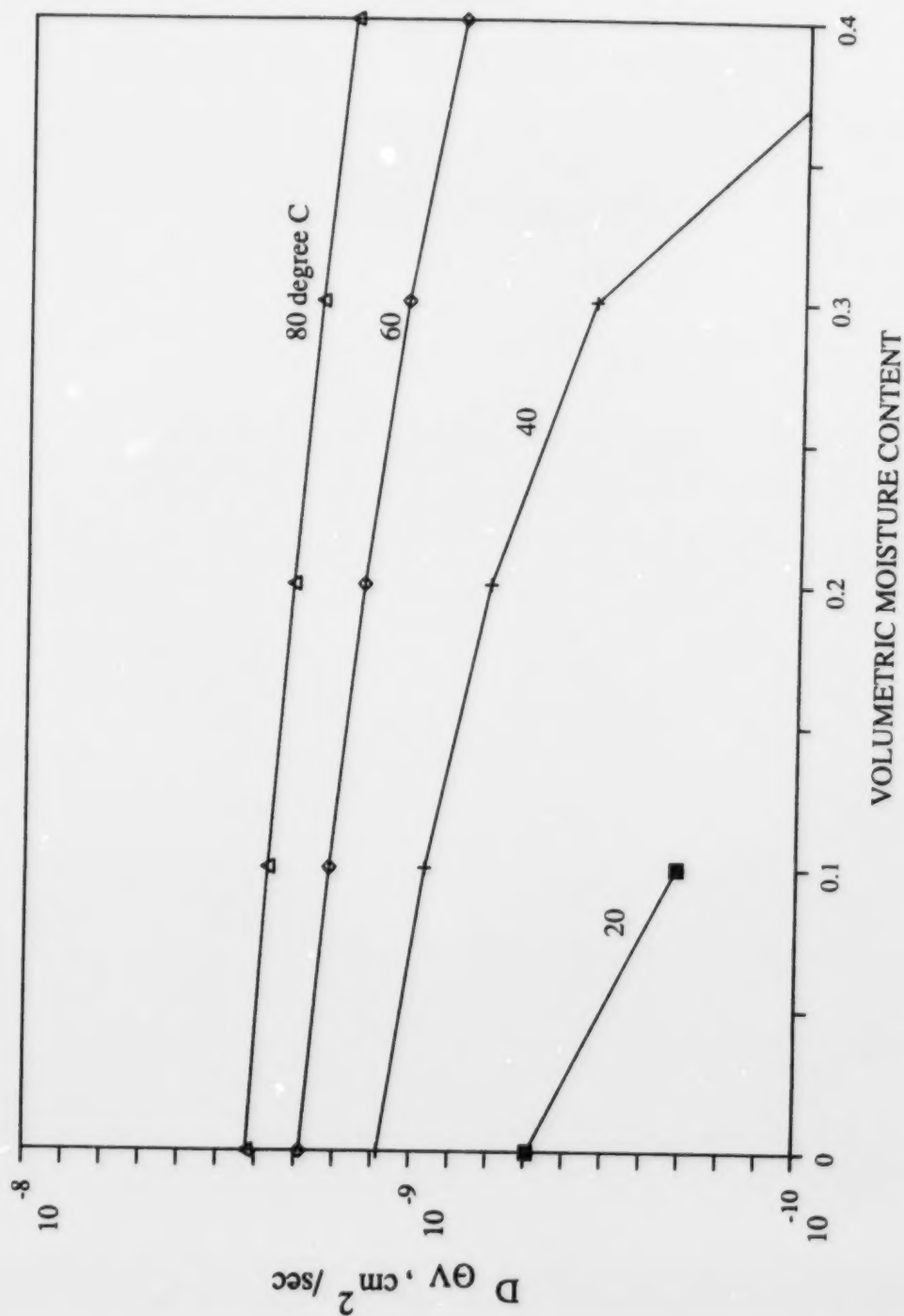
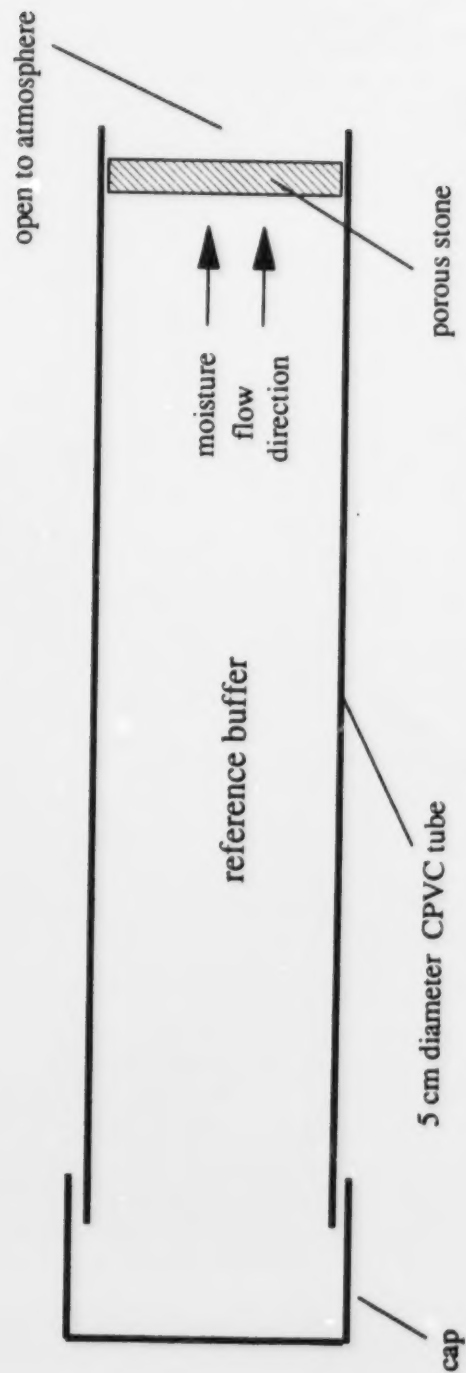


Figure 7 The $D_{\Theta V}$ values - Carleton University



Note: The amount of moisture loss with time is determined by weighing the setup with time.

Figure 8 Test setup to determine the D_{Θ} values of the buffer

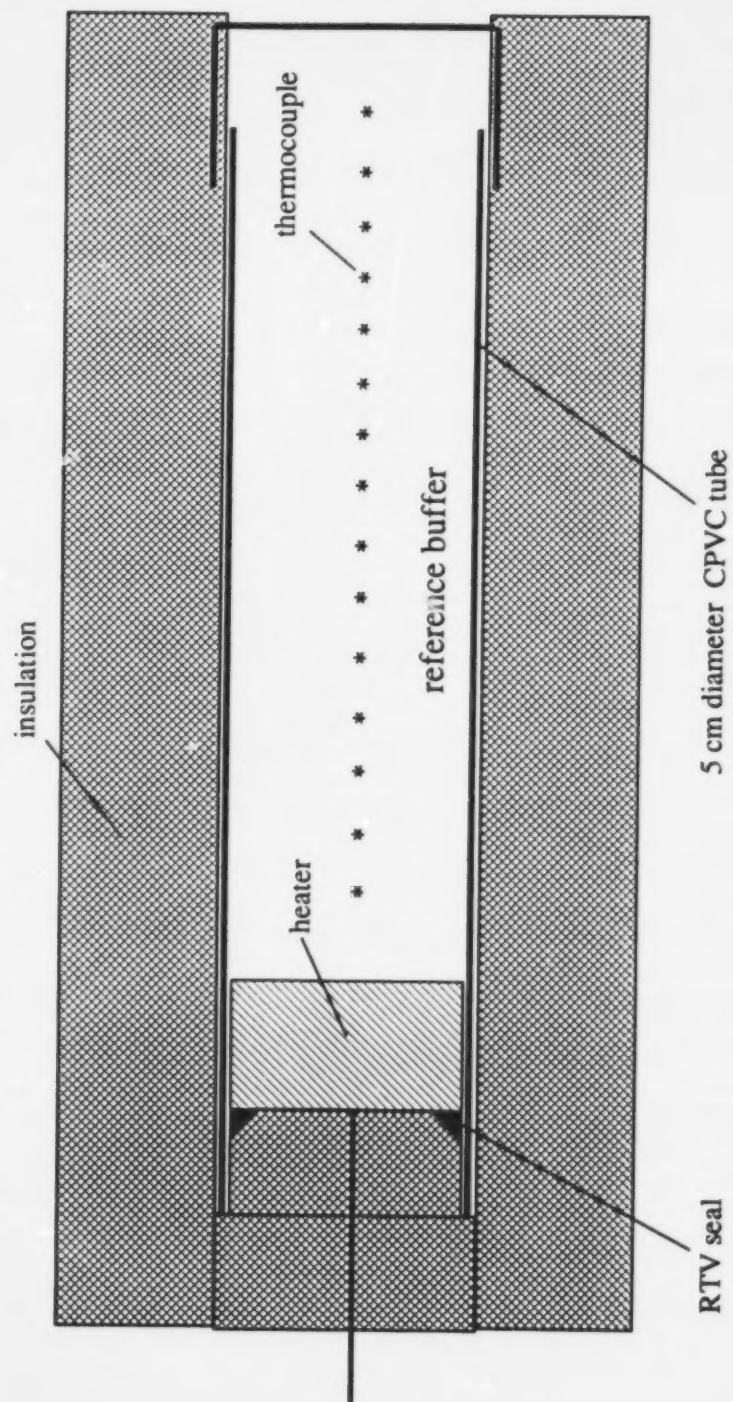


Figure 9 Test setup to determine the D_T values of the buffer

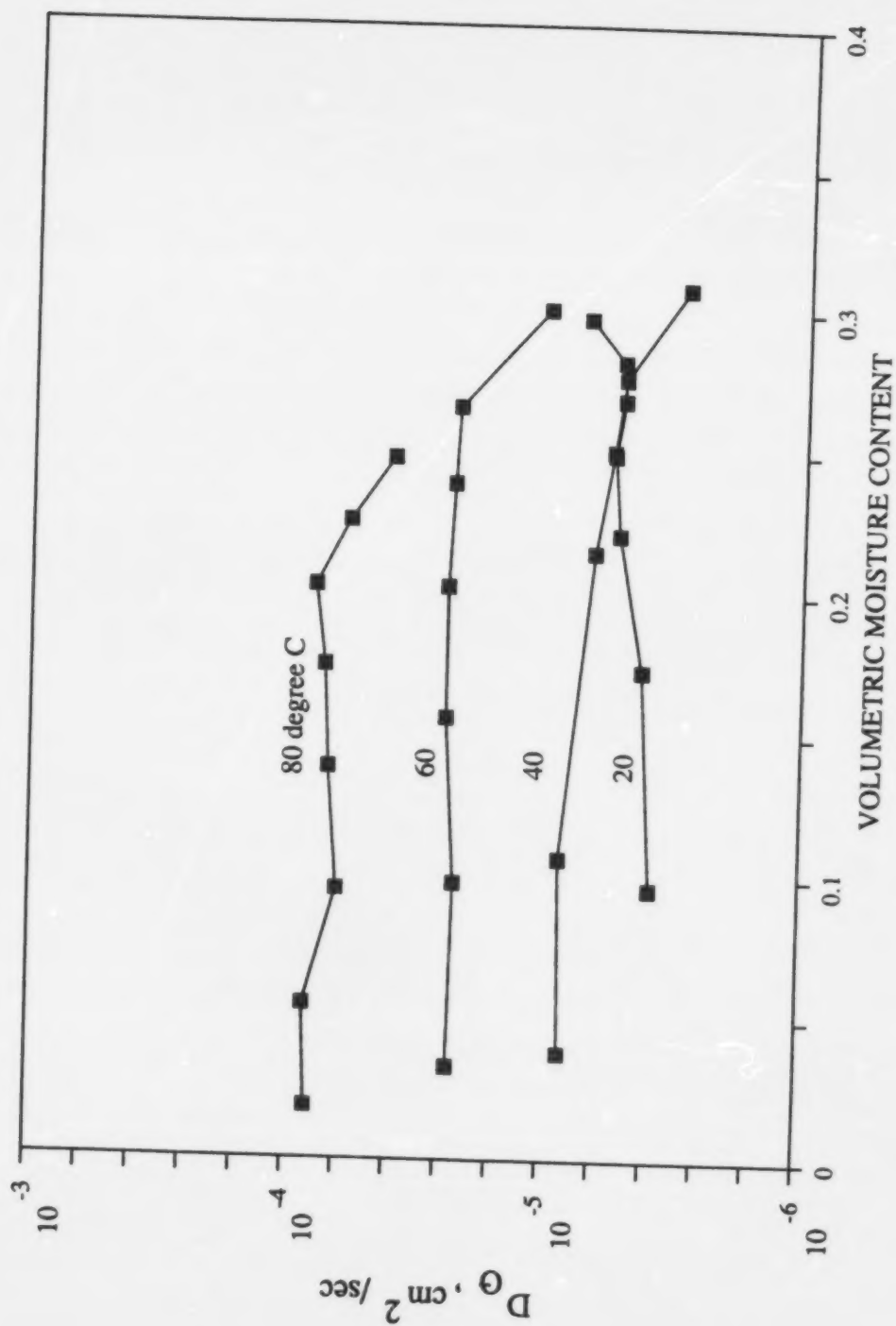


Figure 10 The D_G values - Ontario Hydro

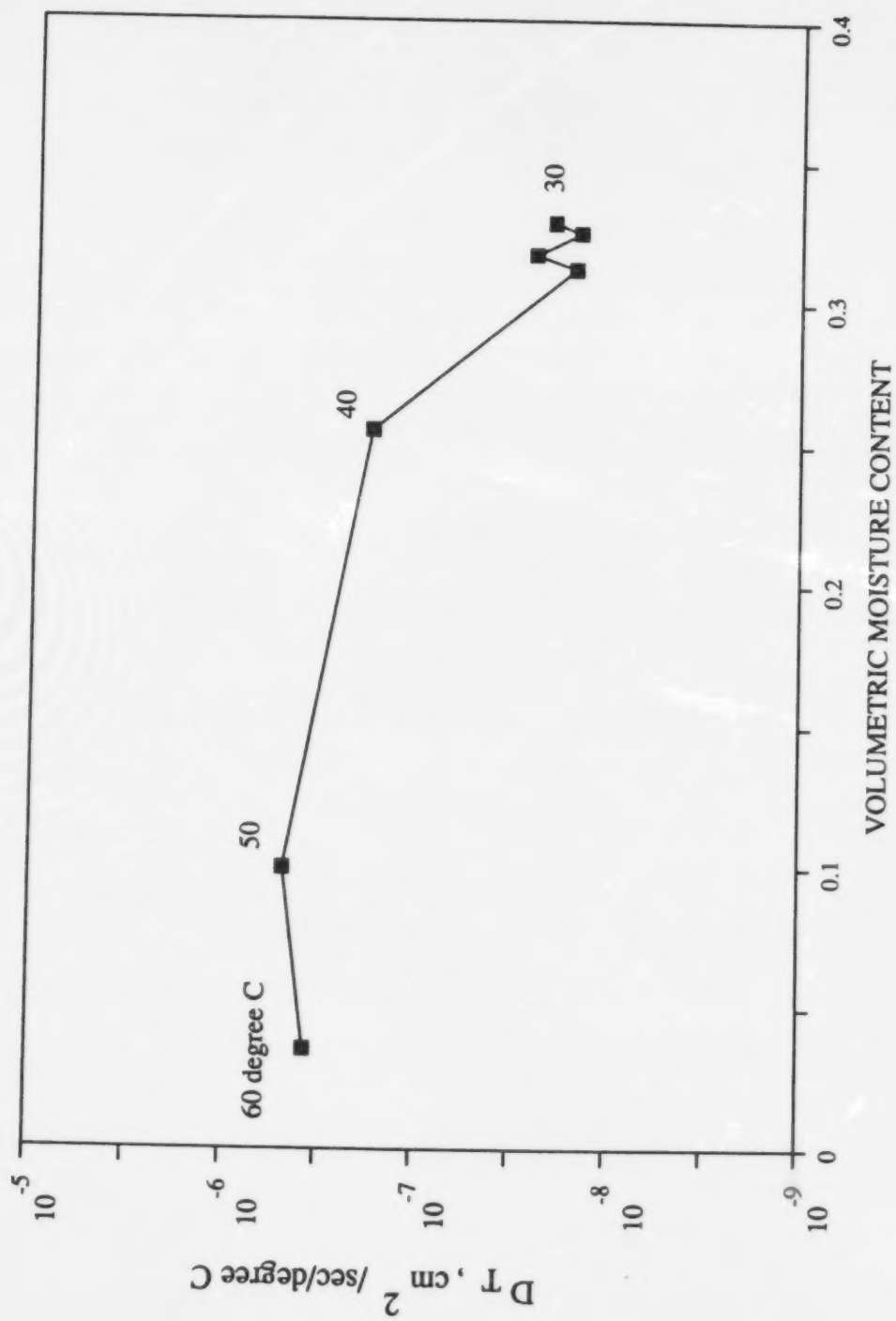


Figure 11 The D_T values - Ontario Hydro

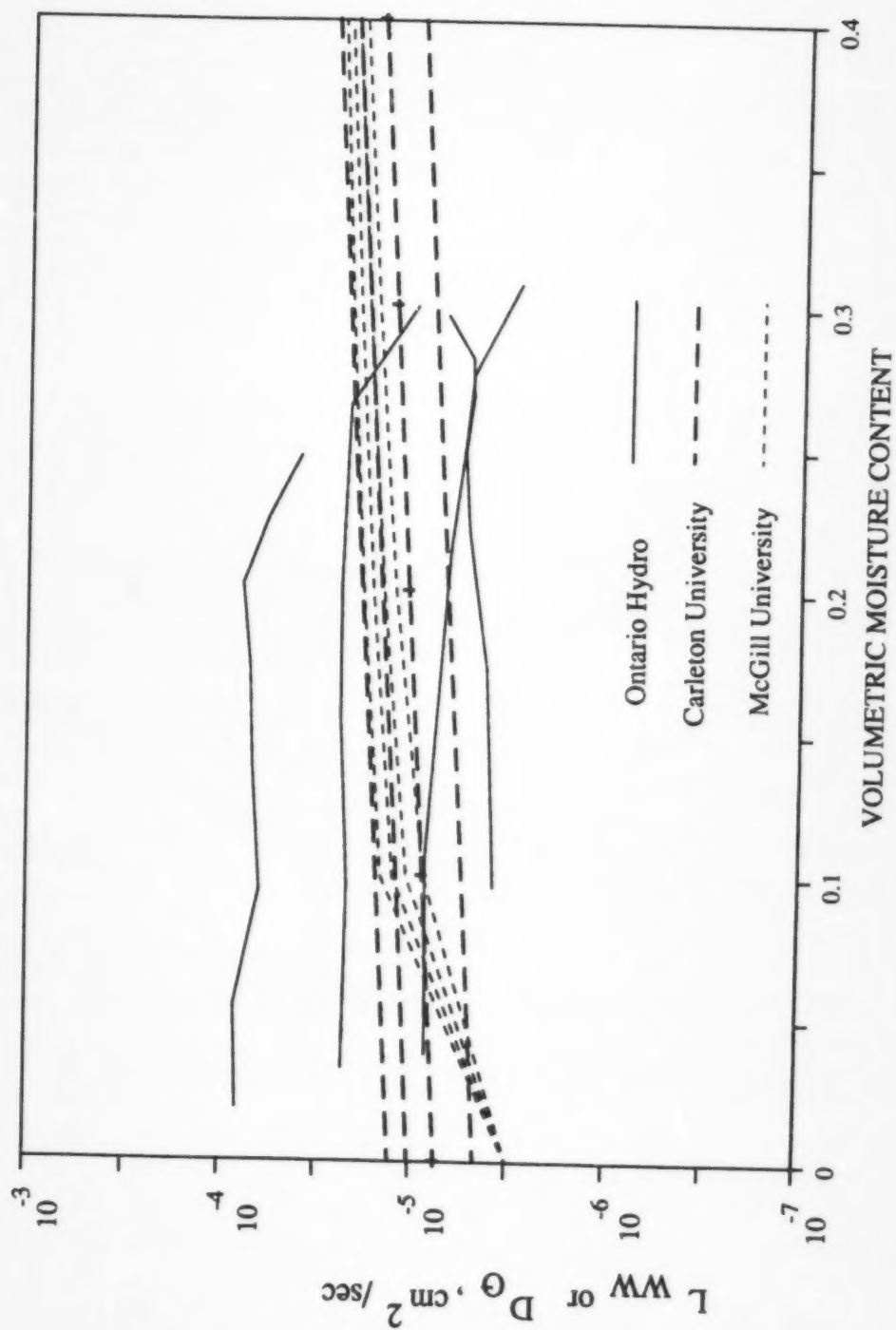


Figure 12 The D_{Θ} or L_{WW} values

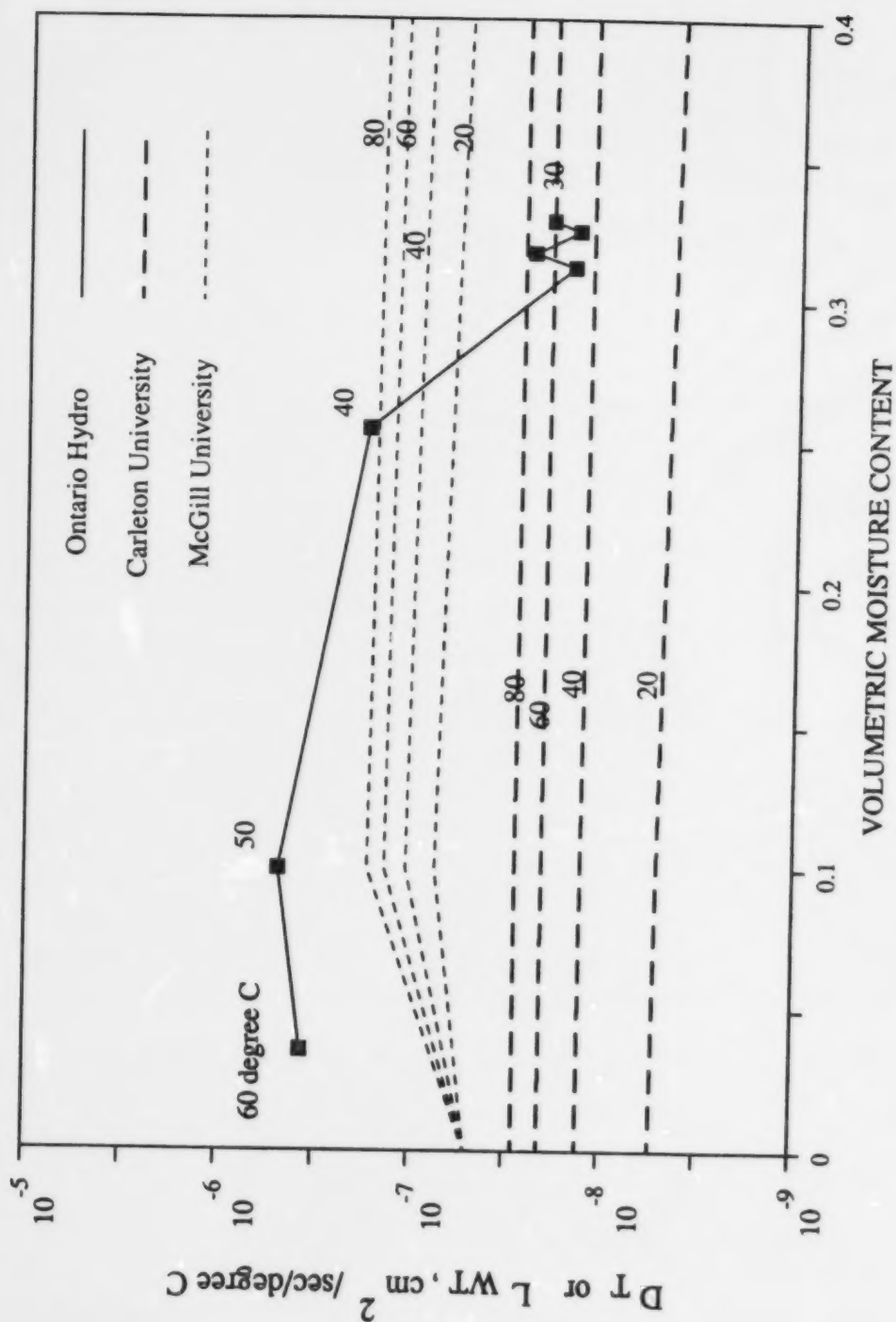


Figure 13 The D_T or $L WT$ values

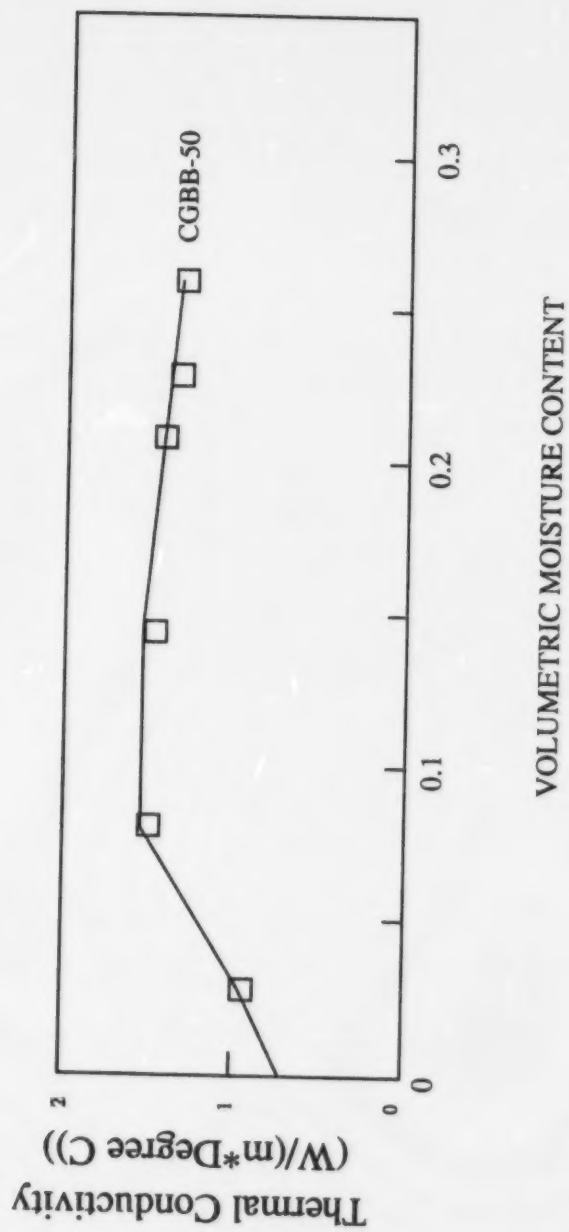


Figure 14 The thermal conductivity of the reference buffer.

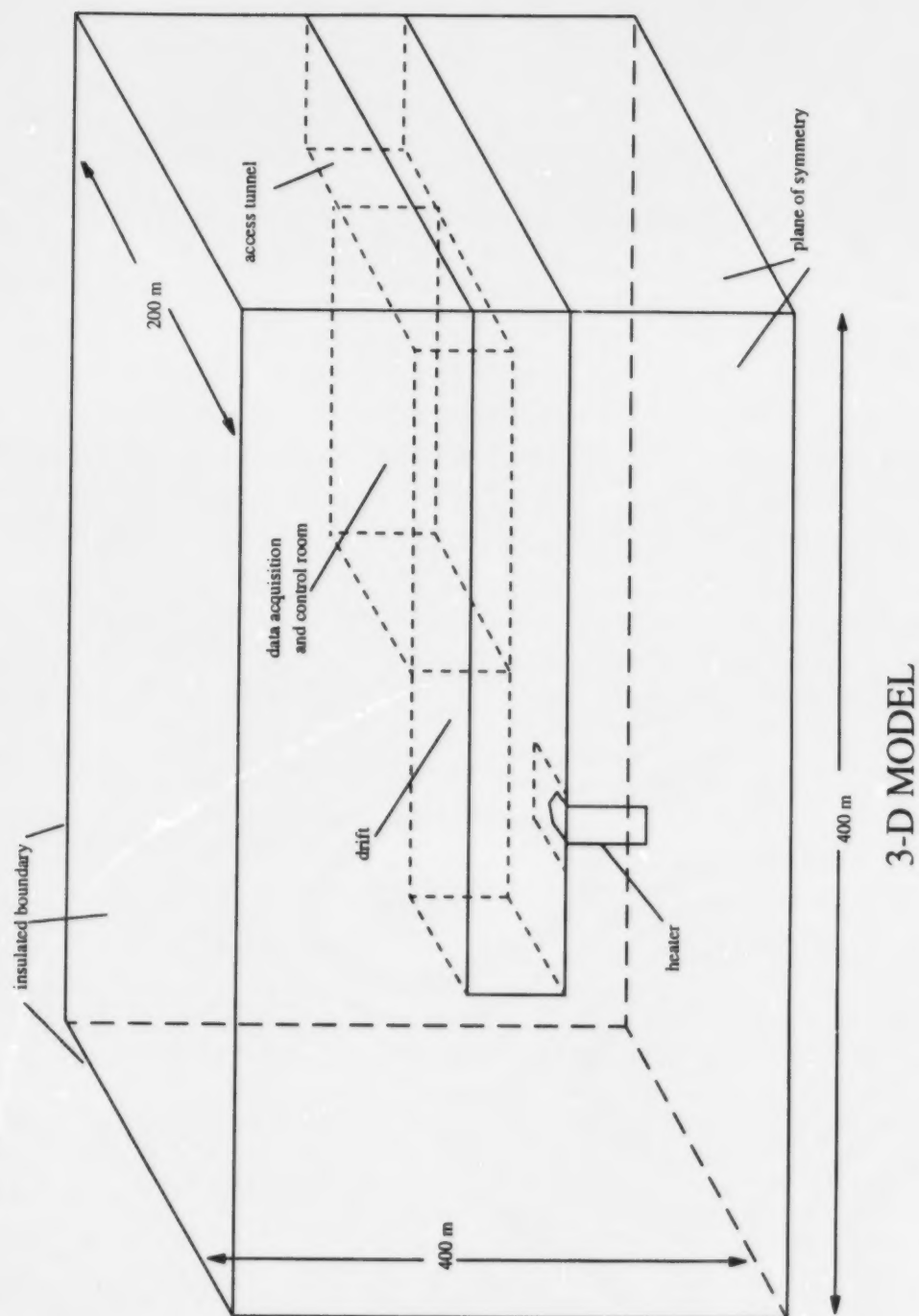


Figure 15 Far-field model

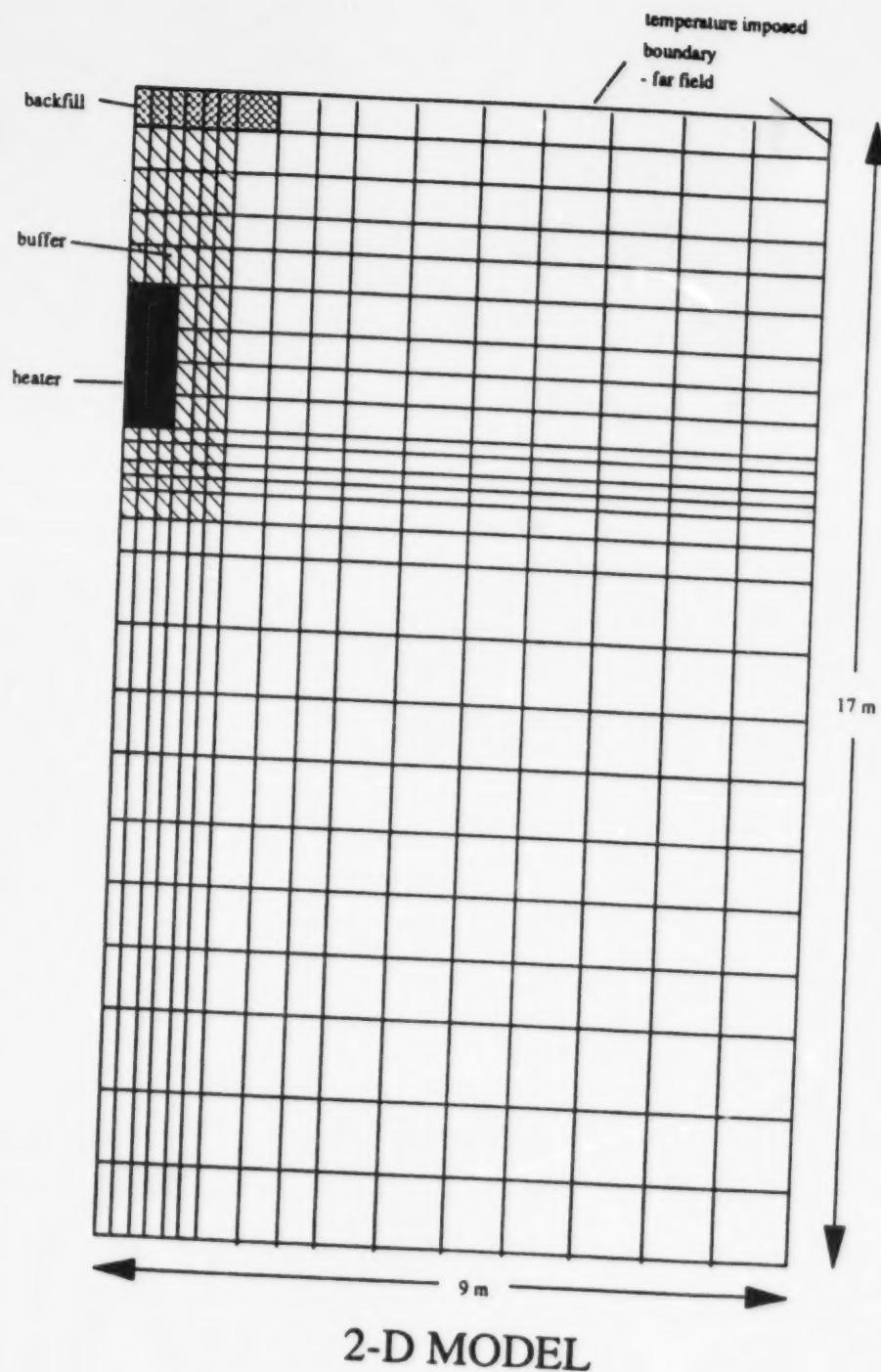


Figure 16 Near-field model

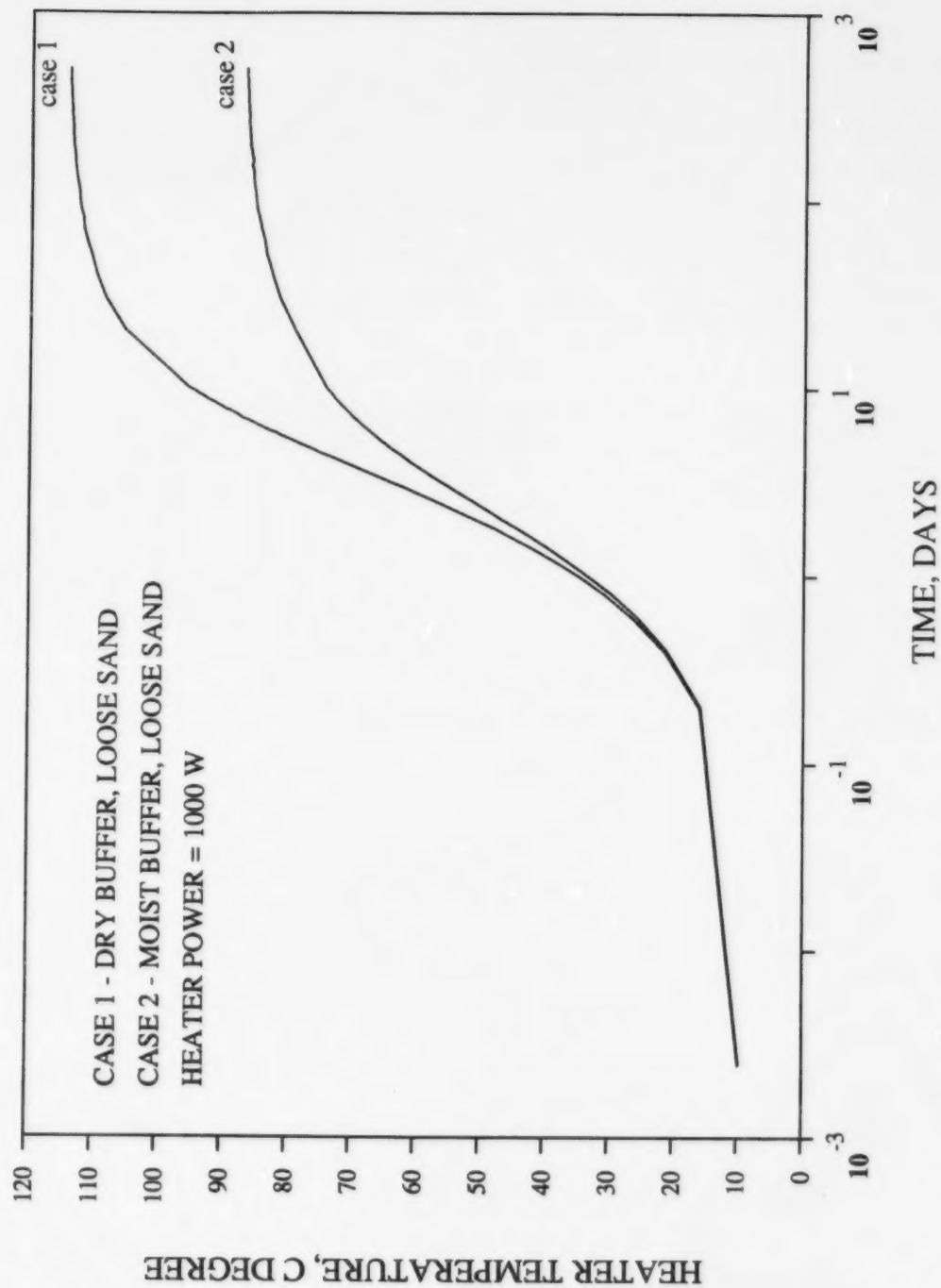


Figure 17 Effect of the thermal conductivity of the buffer.

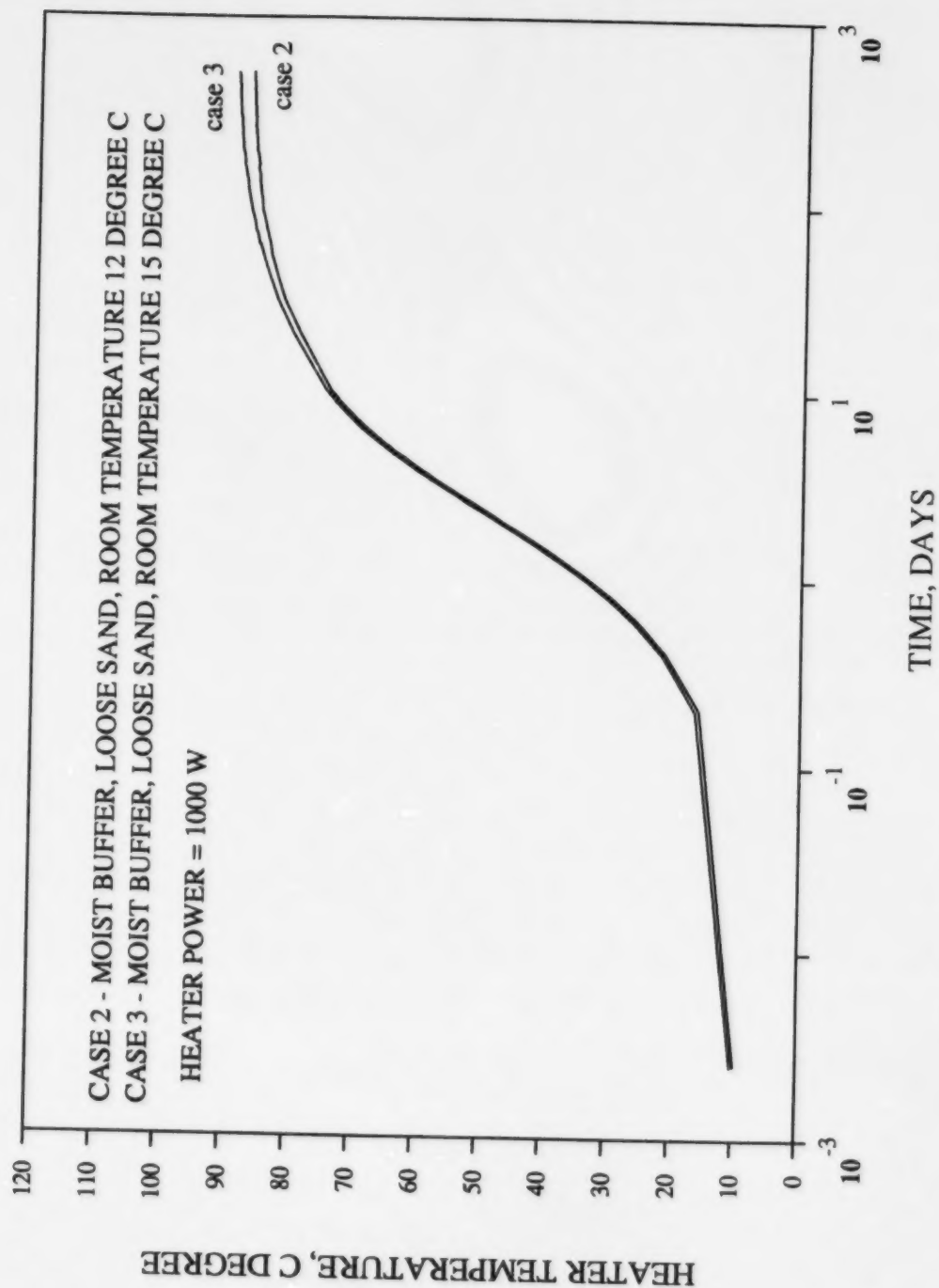


Figure 18 Effect of temperature at the experimental room.

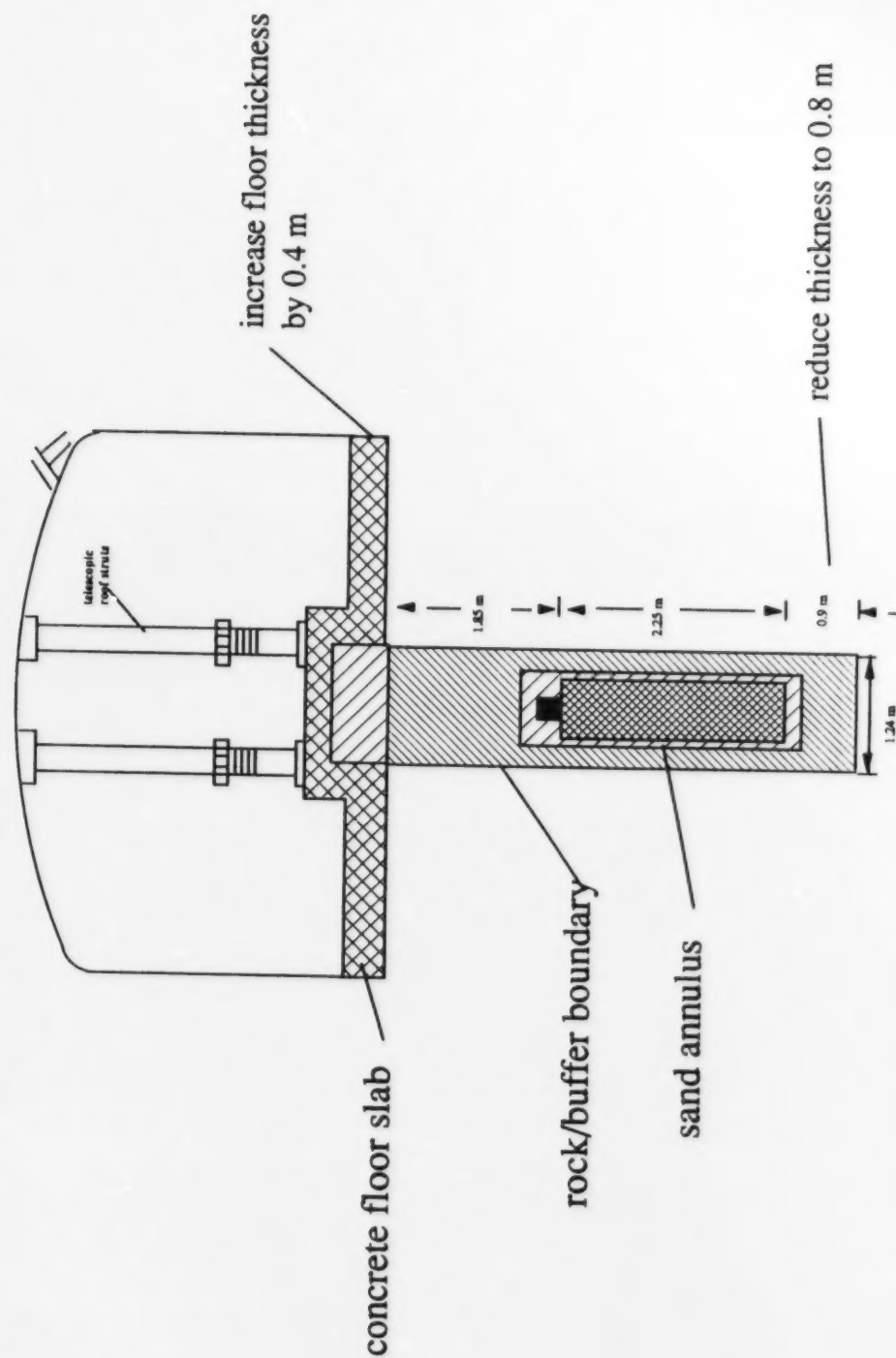


Figure 19 Proposed revision in test #1 geometry.

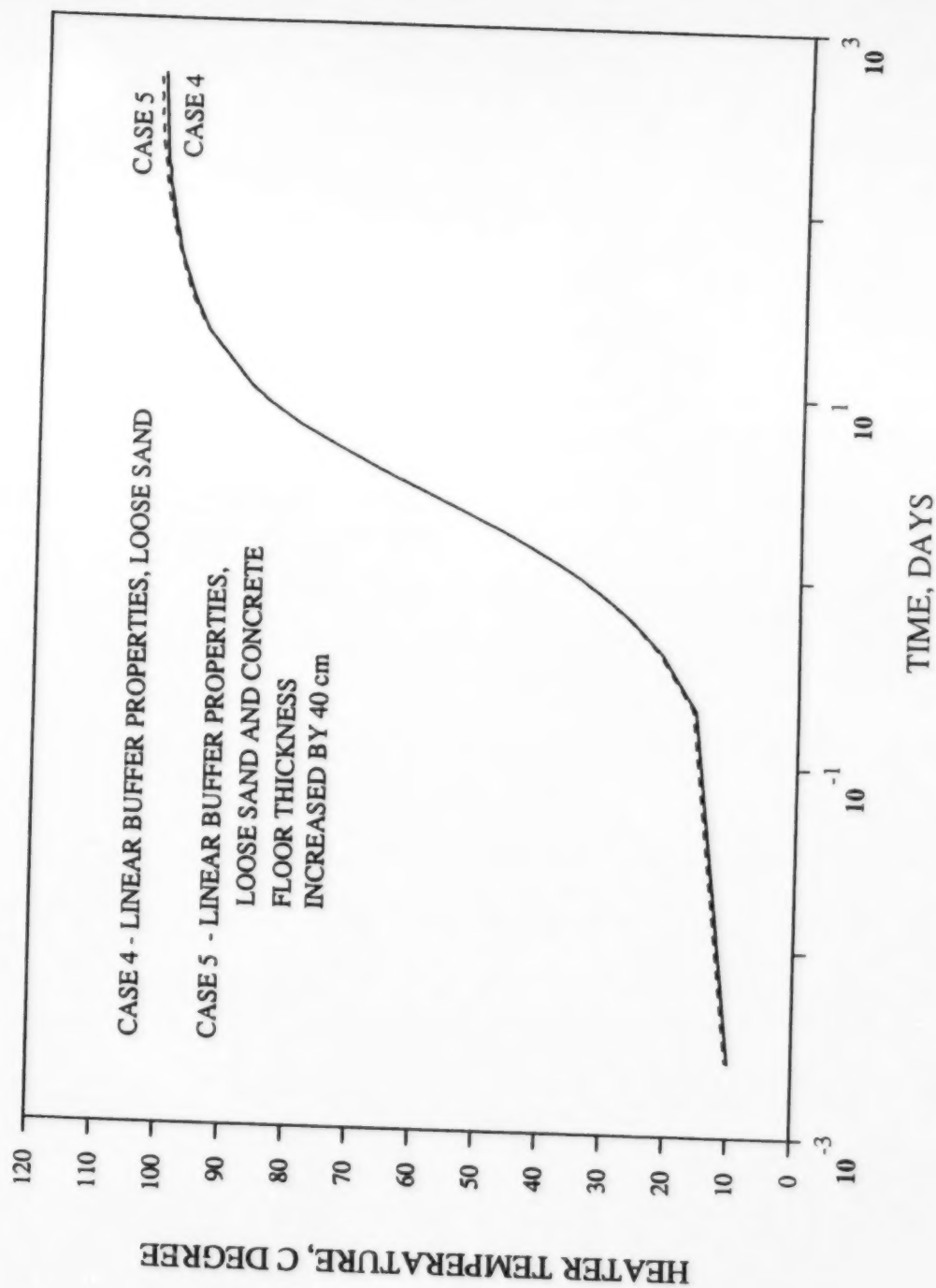


Figure 20 Effect of test geometry.

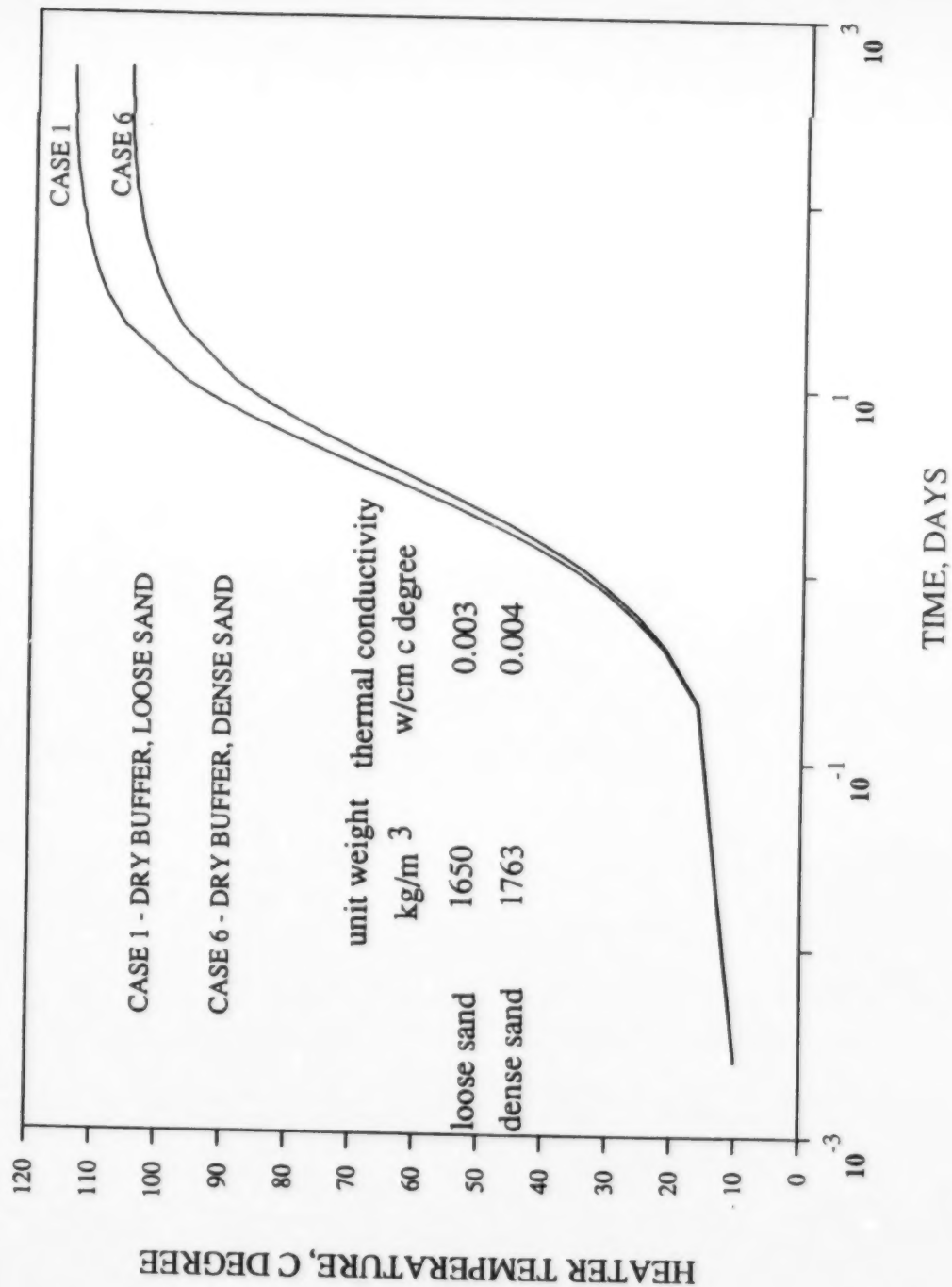


Figure 21 Effect of thermal conductivity of the sand annulus.

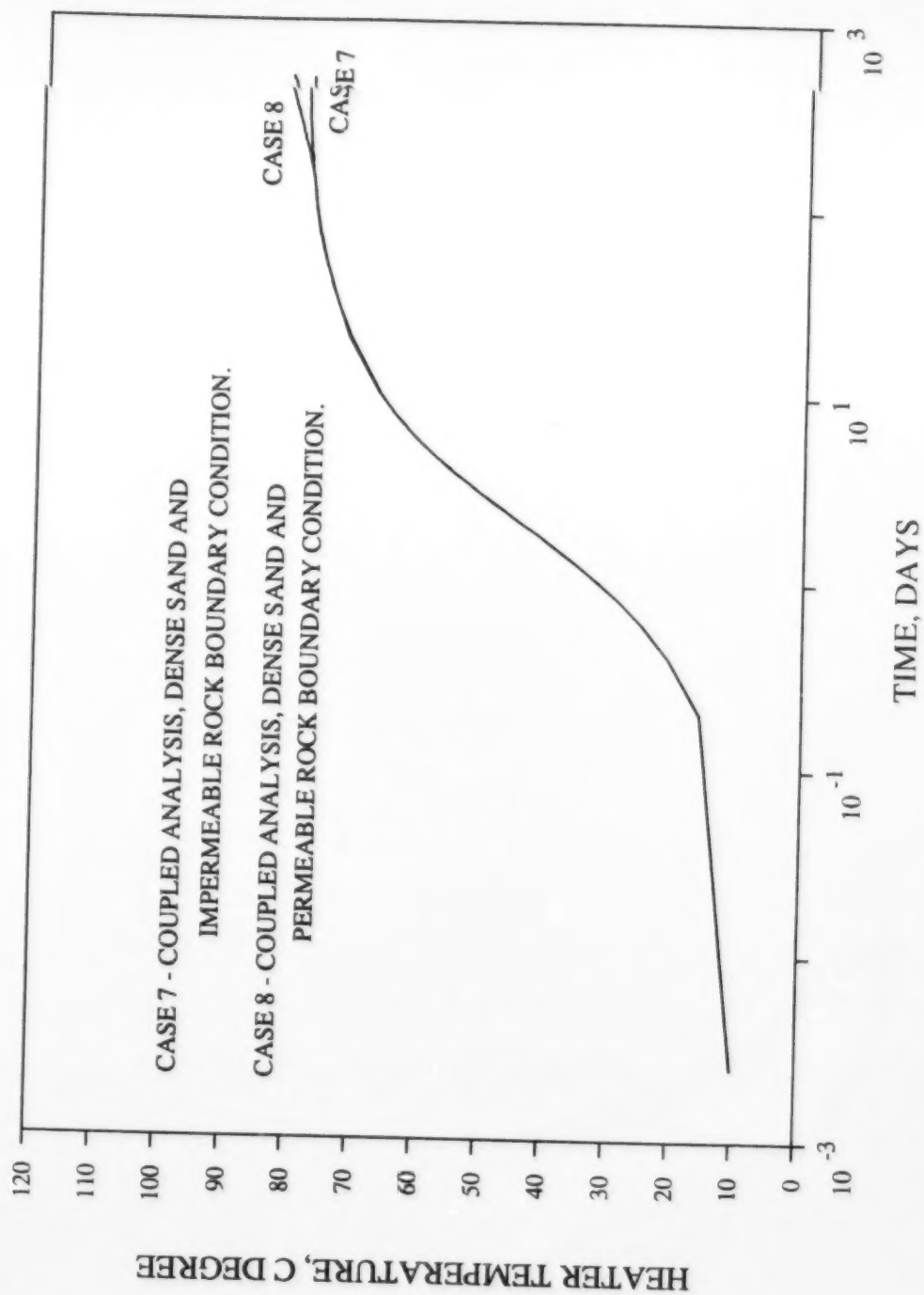


Figure 22 Effect of the hydraulic boundary condition at the buffer/rock interface.

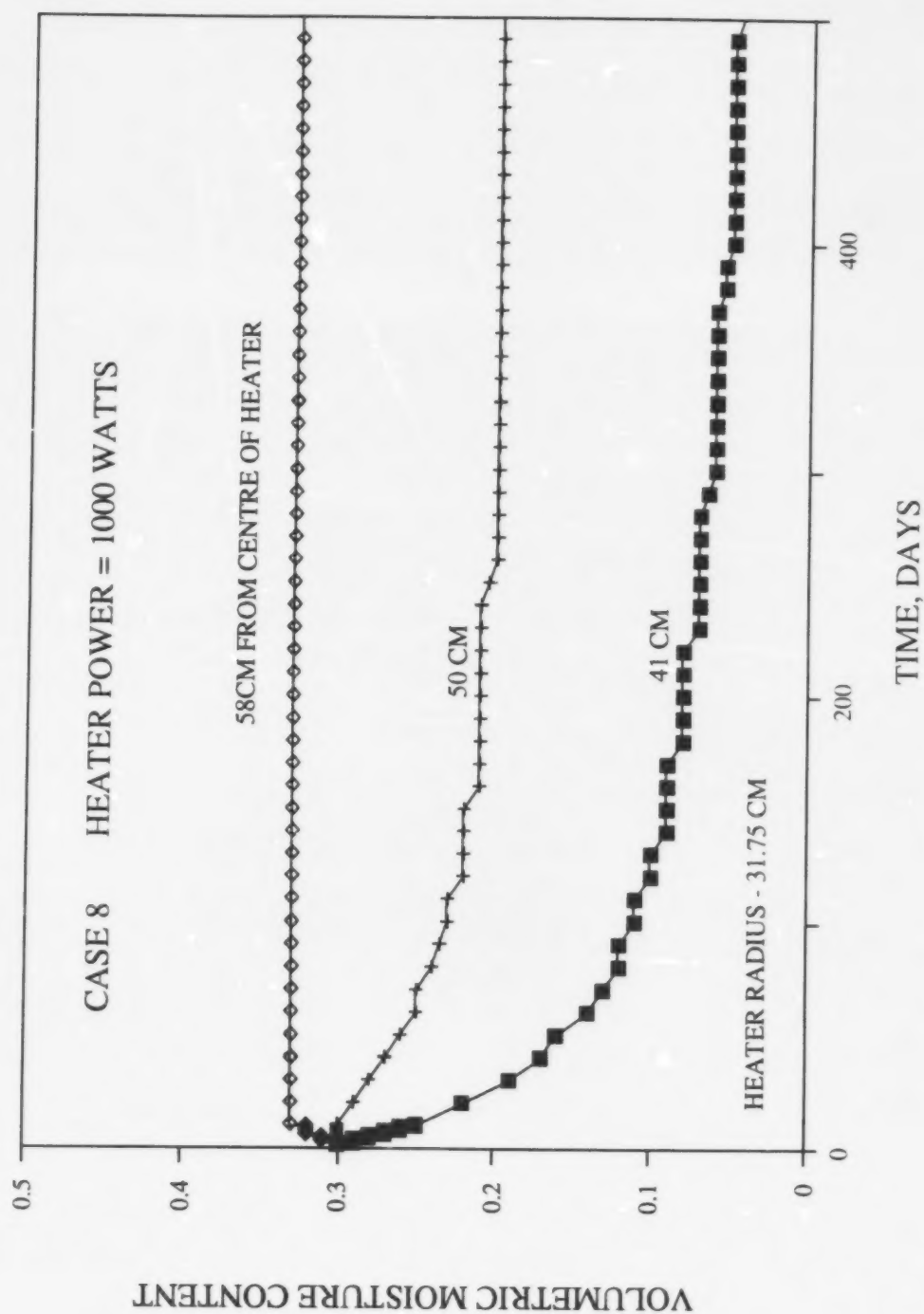


Figure 23 Volumetric moisture content vs. time - Case 8.

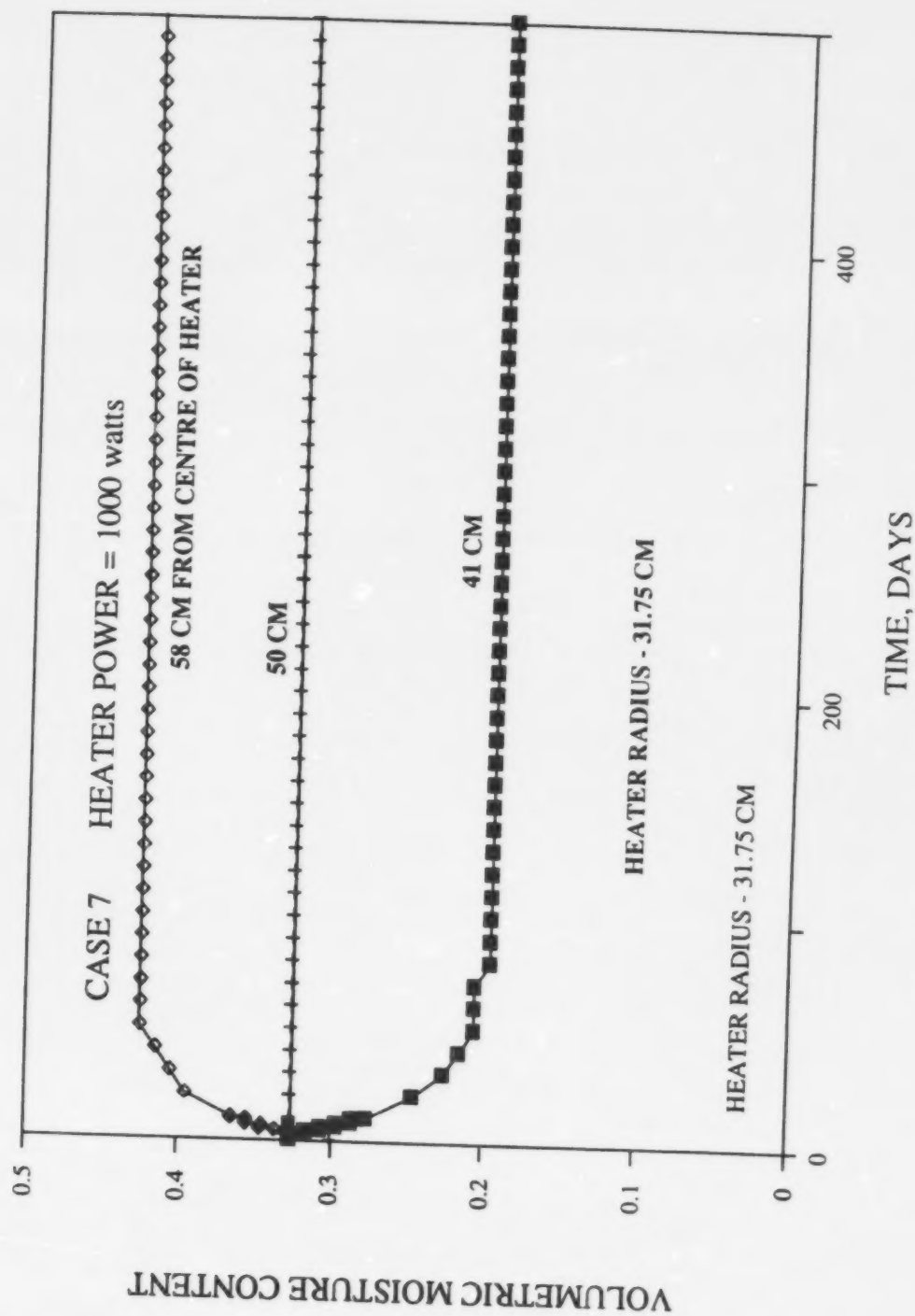


Figure 24 Volumetric Moisture Content vs. Time - Case 7.

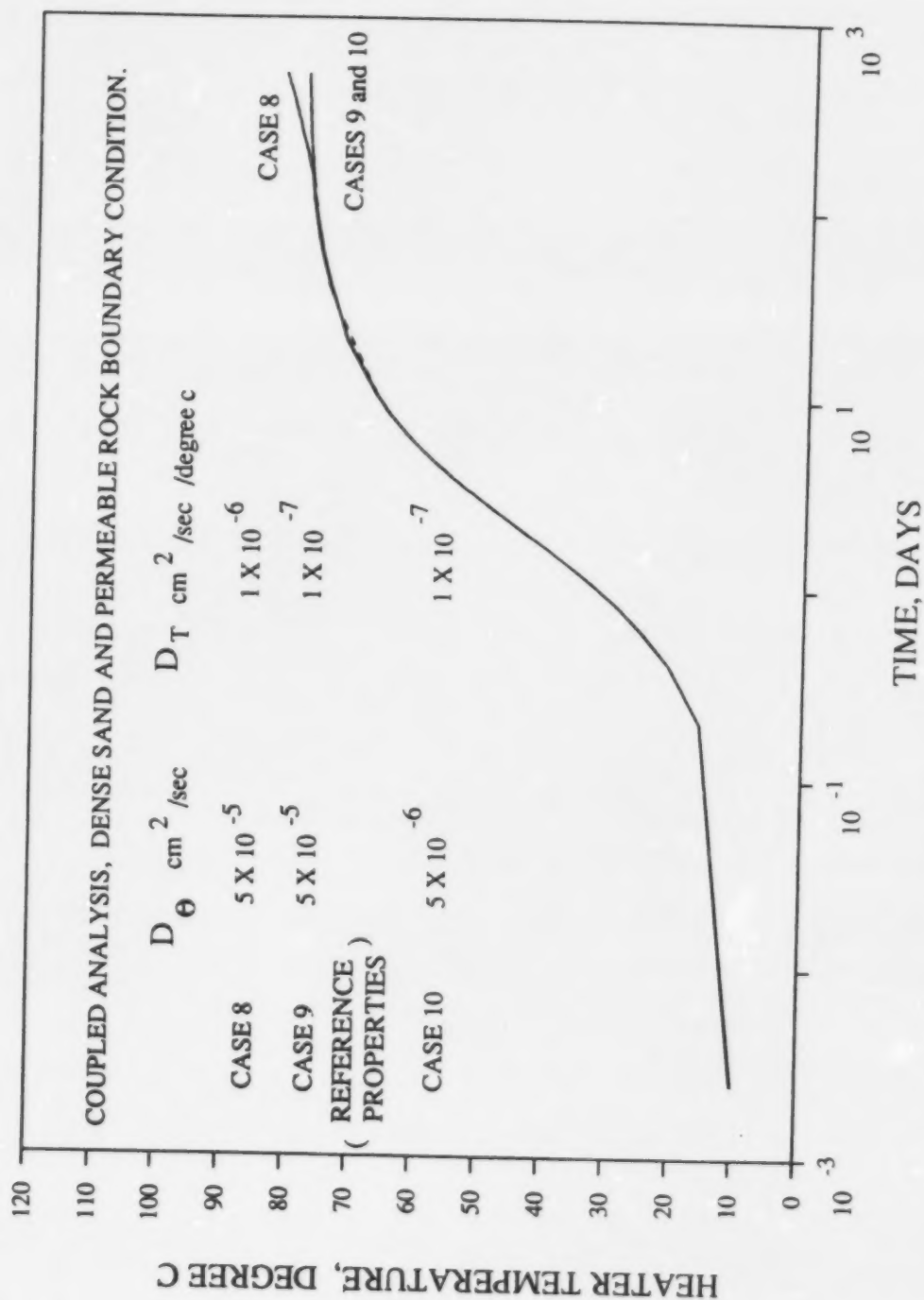


Figure 25 Effect of the thermohydraulic buffer properties.

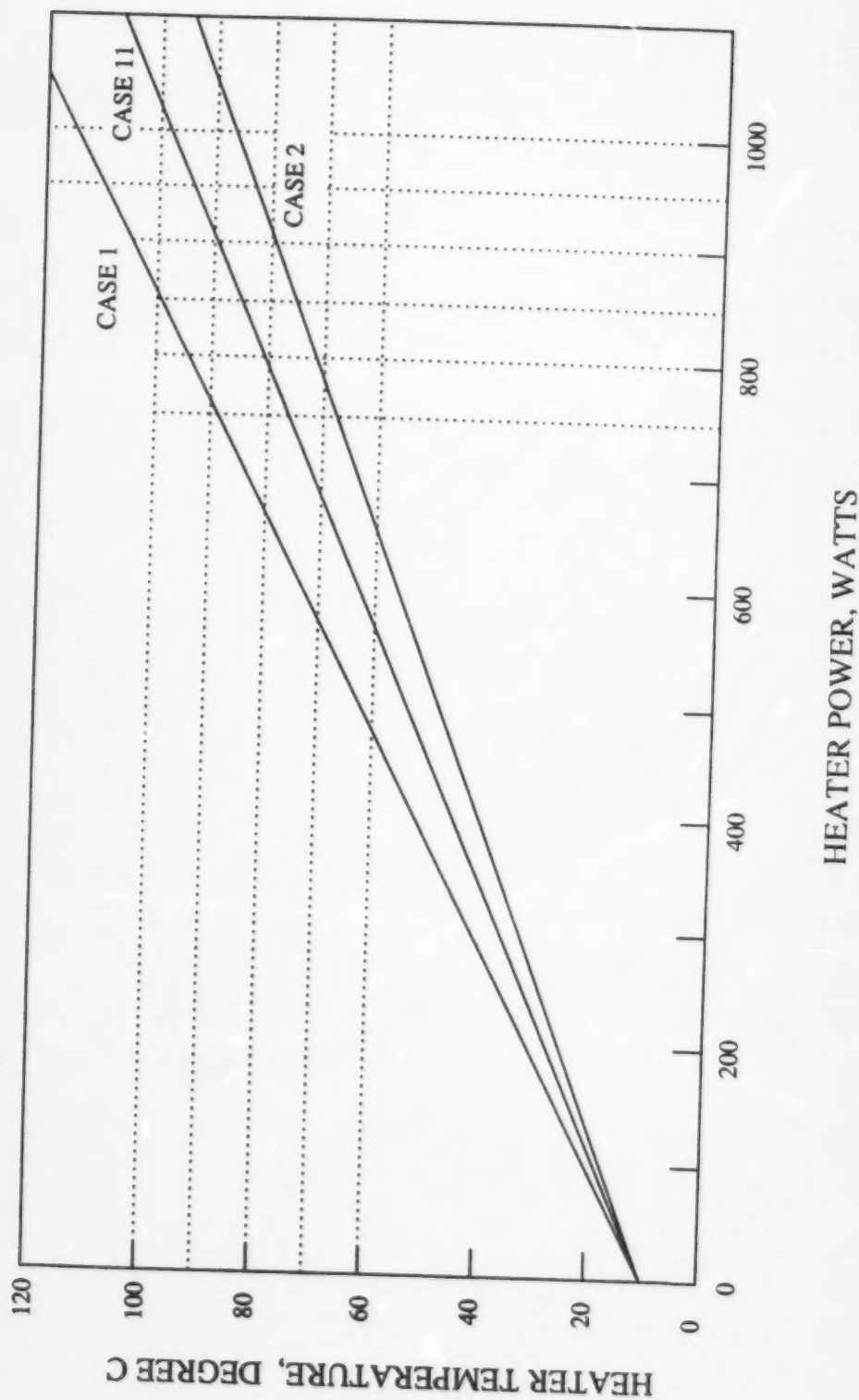


Figure 26 Heater power output vs. maximum heater temperature after 500 days.

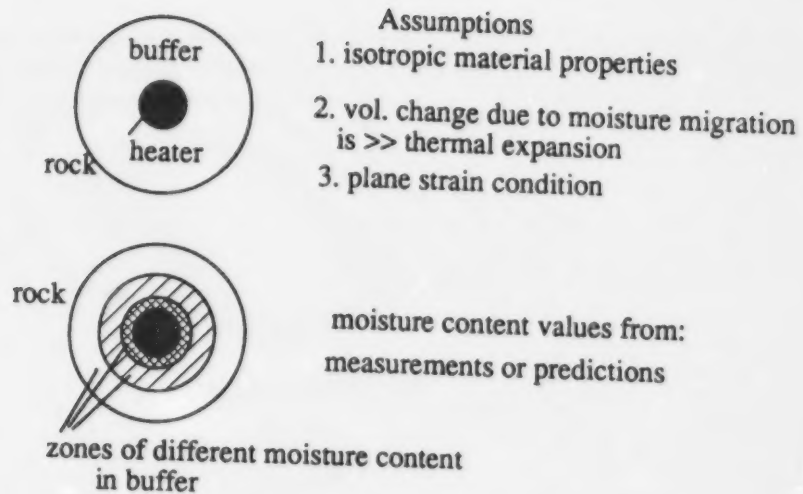


Figure 28 Concentric ring model - Region I.

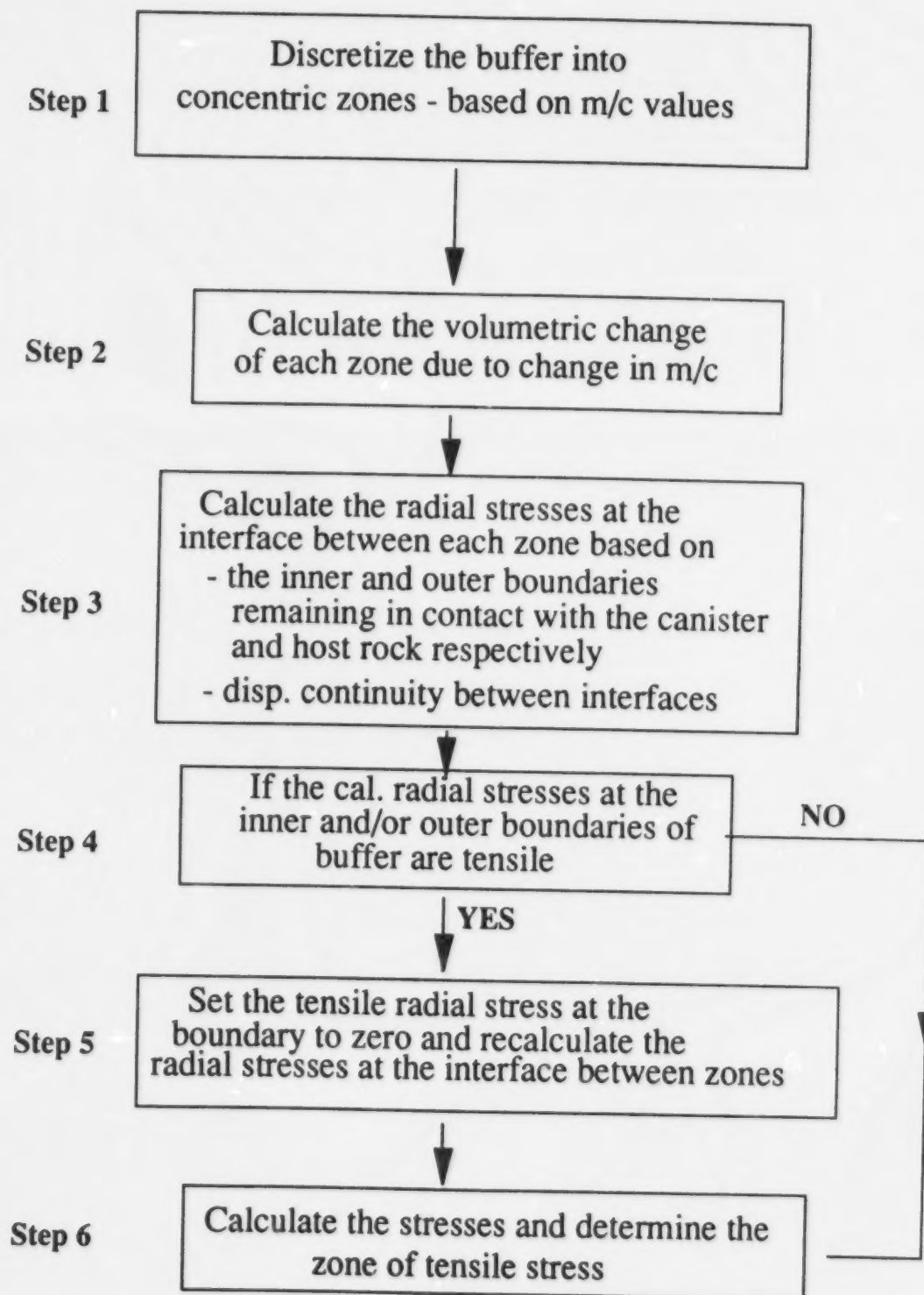
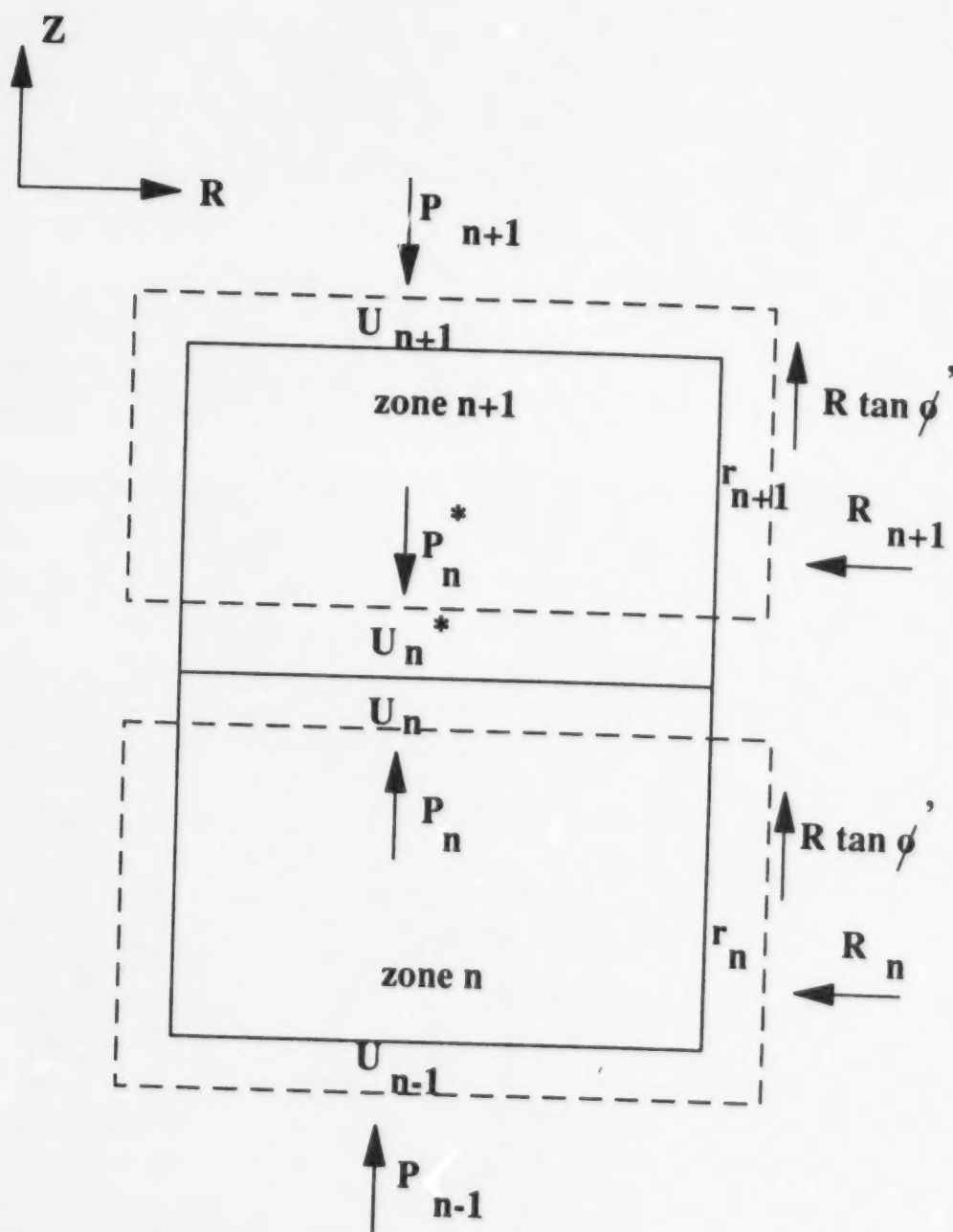


Figure 29 Calculation procedures - concentric ring model.



assumptions

1. isotropic material properties
2. vol. change due to m/c migration is $\gg$ thermal expansion
3. uniform deformation in the Z direction

Figure 30 Radial symmetric disc model - Region II

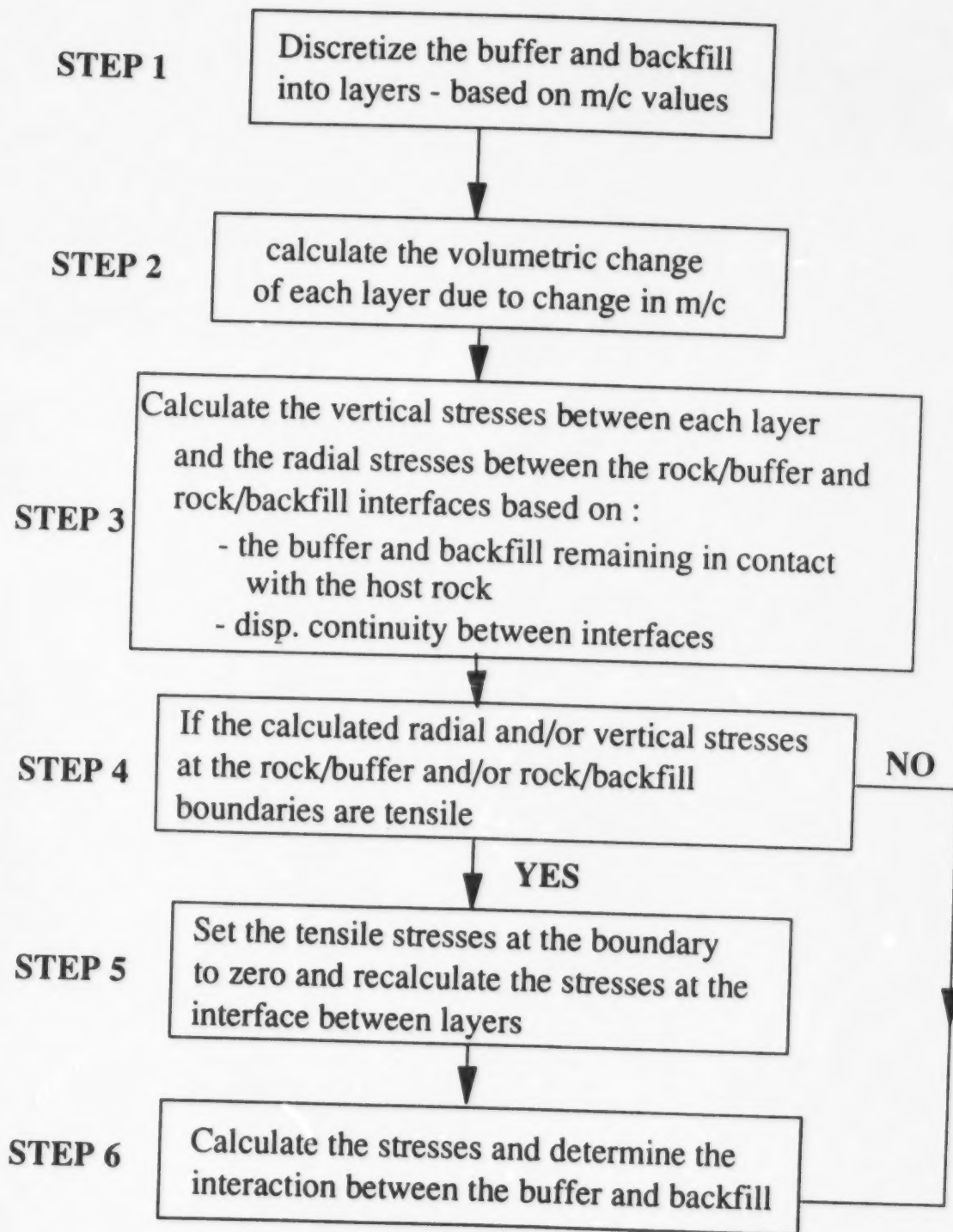


Figure 31 Calculation procedures - radial symmetric disc model.